

# **CORAL REEFS AND THE TSUNAMI OF 26 DECEMBER 2004: GENERATING PROCESSES AND OCEAN-WIDE PATTERNS OF IMPACT**

BY

THOMAS SPENCER

## **INTRODUCTION**

The Indian Ocean tsunami of December 26, 2004 was the most catastrophic such event in recent history, killing more than 230,000 people in the near field and a further 70,000 in the Indian Ocean far field. This death toll was far in excess of the estimated 36,500 deaths associated with the tsunami waves generated by the cataclysmic explosion of Krakatau on August 26-27, 1883 (Abercromby et al., 1888; Winchester, 2003). It was also quite clearly the best-documented tsunami of all time, both scientifically and in terms of the very real human tragedies delivered in almost real-time by the global communications revolution. Scientific data gathered to understand this event, and thus to better predict future such catastrophes, have included not only the application of now well-established techniques at the local-to-regional spatial scale such as the remote sensing of coastal margins (CRISP, 2005) and ocean-surface heights (NOAA, 2005a), multibeam swath bathymetry of the earthquake zone (Wilson, 2005) and handheld GPS-controlled surveys both above and below water but also the products of newly emerging technologies at the global scale such as the spectacular seismic monitoring delivered by the Global Seismographic Network (Park et al., 2005a) of digital broadband, high dynamic range seismometers, the pattern of large-scale displacements revealed by the network of 41 continuously recording GPS stations throughout Southeast Asia (Bannerjee et al., 2005) and the detection of earthquake and tsunami-induced deep infrasound in the central Indian Ocean (Garces et al., 2005).

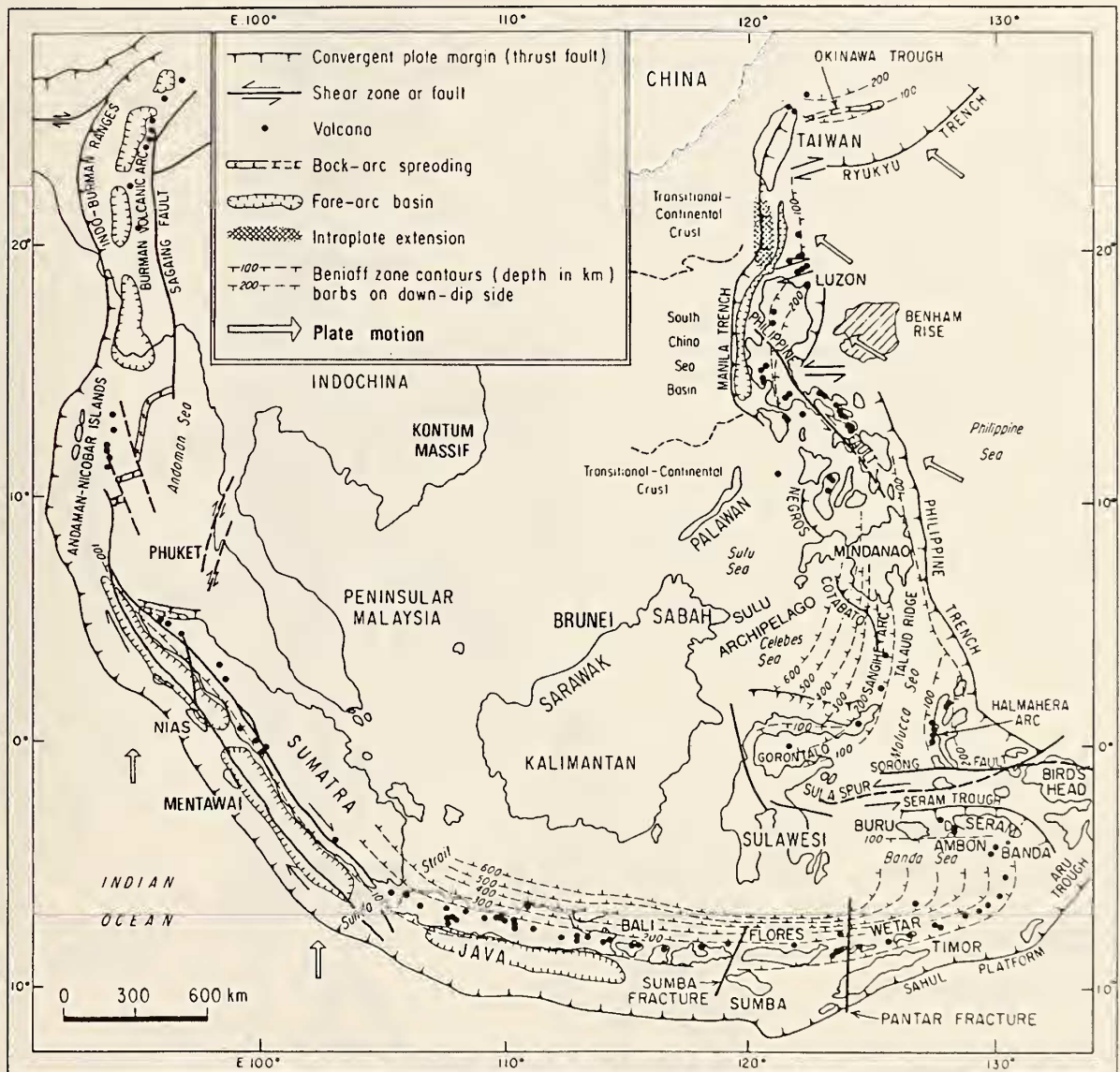
It has also been the best mathematically modelled, simulated and visualized tsunami in history. At the same time, it has not always been easy to establish common points of reference between the many nation states impacted by the disaster, to set detailed local studies within wider regional pictures and to separate out anecdotal reports from scientific facts. This paper attempts to place the December 2004 tsunami in its contemporary, historical and possible near-future tectonic contexts. It also attempts to provide a regional synthesis which highlights the regional variability in tsunami wave characteristics. It is hoped that individual site reports on tsunami impacts of coral reefs and associated shallow marine ecosystems can be placed within this framework and thus better understood.

## WHY, WHERE AND WHY NOW: THE PLATE TECTONIC FRAMEWORK

Southeast Asia is characterized by the convergence of the oceanic Indo-Australian plate, at an average rate of  $7.0 \text{ cm a}^{-1}$  in the direction  $003^\circ$ , with the extension of the continental Eurasian plate comprising the Malay Peninsula, Sumatra, the Sunda Shelf sea and parts of Borneo (Simandjuntak and Barber, 1996). Where the two plates meet, the oceanic plate is subducted beneath the continental plate. This tectonic setting is expressed in a nearly continuous arc of volcanic and non-volcanic islands and associated deep-water trench and back-arc basins, which extends from Myanmar and the collision zone with India and the Himalayas to Timor and the collision zone of Sumatra's outer-arc ridge with Papua and Australia (Fig. 1; Hutchinson, 2005). The character of convergence changes from east-to-west. In the east, south of Java, relatively old (ca. 100 Ma) oceanic lithosphere is subducted in a direction perpendicular to the trench orientation. However, to the northwest, the relatively young (ca. 40 Ma) oceanic lithosphere behaves rather differently. Not only does the convergence rate reduce (from  $7.8 \text{ cm a}^{-1}$  at Sumbawa to  $6.0 \text{ cm a}^{-1}$  in the Andaman Islands) but the convergence also becomes increasingly oblique (Fitch, 1972). Thus convergence needs to be partitioned into two components comprising both trench-normal subduction and forces parallel to the trench which generate strike-slip motions along major fault systems (Fig. 2; McCaffrey, 1996). As a result of these dynamics, a sliver plate, the Burma plate, has sheared off parallel to the subduction zone and sits between the convergent plate margin to the west and great fault systems to the east which comprise (from south-to-north) the Sumatra Fault, the West Andaman Fault (the spreading ridge of the Andaman Sea basin) and the Sagaing Fault in Myanmar (Figs. 1 and 2; Malod and Mustafa Kemal, 1996; Curray, 2005). It was this microplate, and its relations with the Indo-Australian plate, that was involved in the December 2004 tsunami.

In interseismic periods, strain accumulates on the locked fault between the oceanic and continental plates. These stresses are then periodically released in large "megathrust" earthquakes associated with the rupture of this boundary. These earthquakes may in turn generate tsunamis. Tsunami databases variously list 64 tsunami events in the Indian Ocean between 1750 and 2004 (NGDC, 2005) and 87 events between 1640 and 2005 (Siberian Division, Russian Academy of Sciences, 2005). Table 1 lists those earthquakes "definitely" or "probably" (NGDC (2005) terminology, categories 4 and 3) generating tsunamis since 1797 for the section of the Sunda Arc from SW Sumatra ( $5^\circ\text{S}$ ) to the northern Andaman Islands ( $13^\circ\text{N}$ ). Figure 3 shows the location of large historical earthquakes between  $2^\circ$  and  $14^\circ\text{N}$ , historical seismicity 1964-2004 and aftershocks to January 14 following December 26. It is known, for example, that the 1797, 1833 and 1861 earthquakes (Fig. 4) all produced tsunamis both on the islands and the Sumatran coast, as well as resulting in significant vertical adjustments (Newcomb and McCann, 1987). Thus the 1833 earthquake appears as a large emergence event in the fossil coral microatolls on the reefs of Sumatra's outer-arc ridge. Stratigraphic analysis of both fossil and living microatolls has allowed Zachariasen et al. (1999) to identify emergence of 1

to 2 m increasing towards the trench. They argue that this pattern and magnitude of uplift is consistent with about 13 m of slip on the subduction interface and suggest an upwards revision of the magnitude of the earthquake to 8.8-9.2. The December 2004 earthquake and resulting tsunami were, therefore, not unusual historically in terms of location, general characteristics and type of impacts. Where it differed, however, was in the magnitude of those effects, its spatial scale and the complex nature of its energy release.



**Figure 1.** Tectonic setting of Southeast Asia (after Hutchison, 2005).



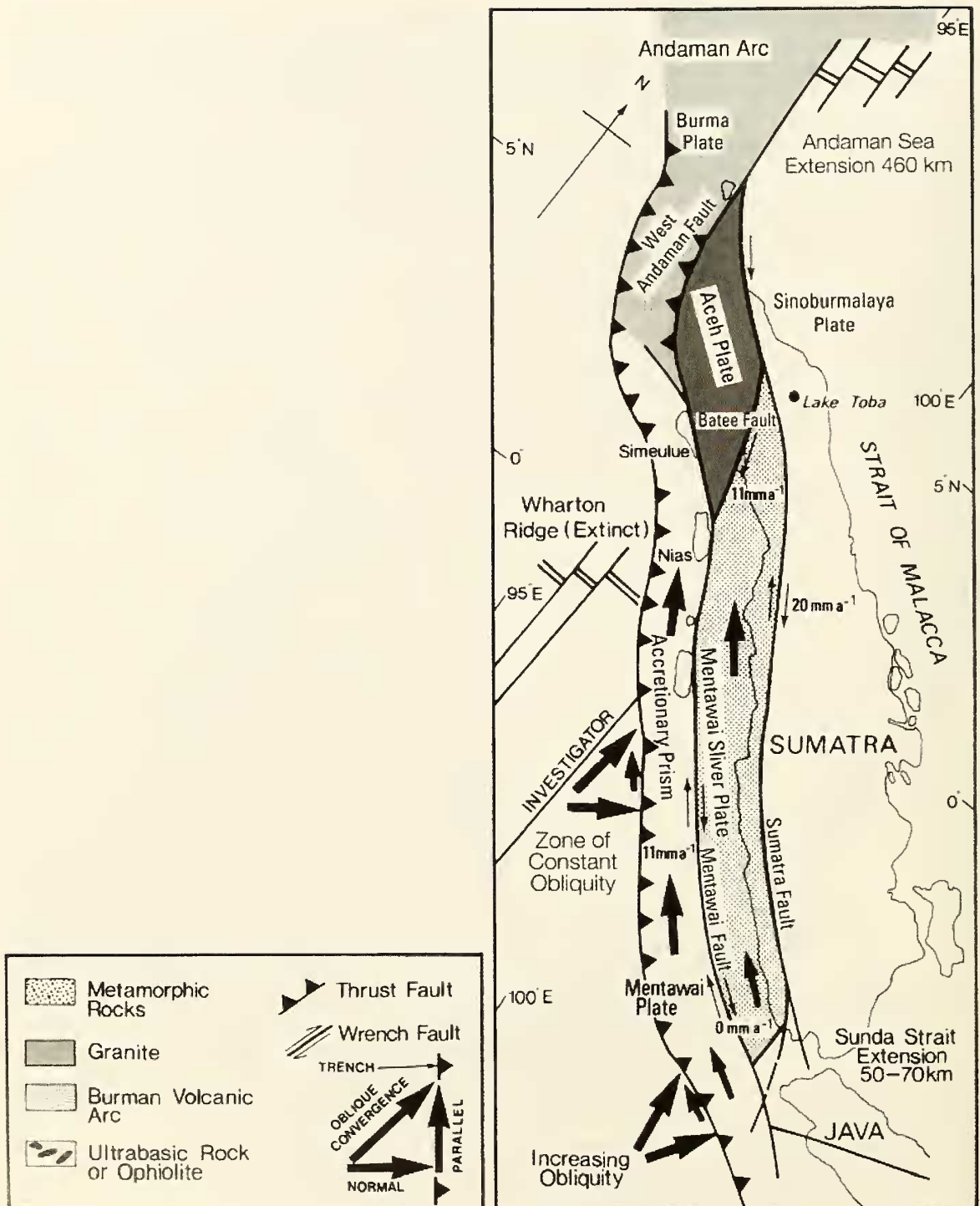
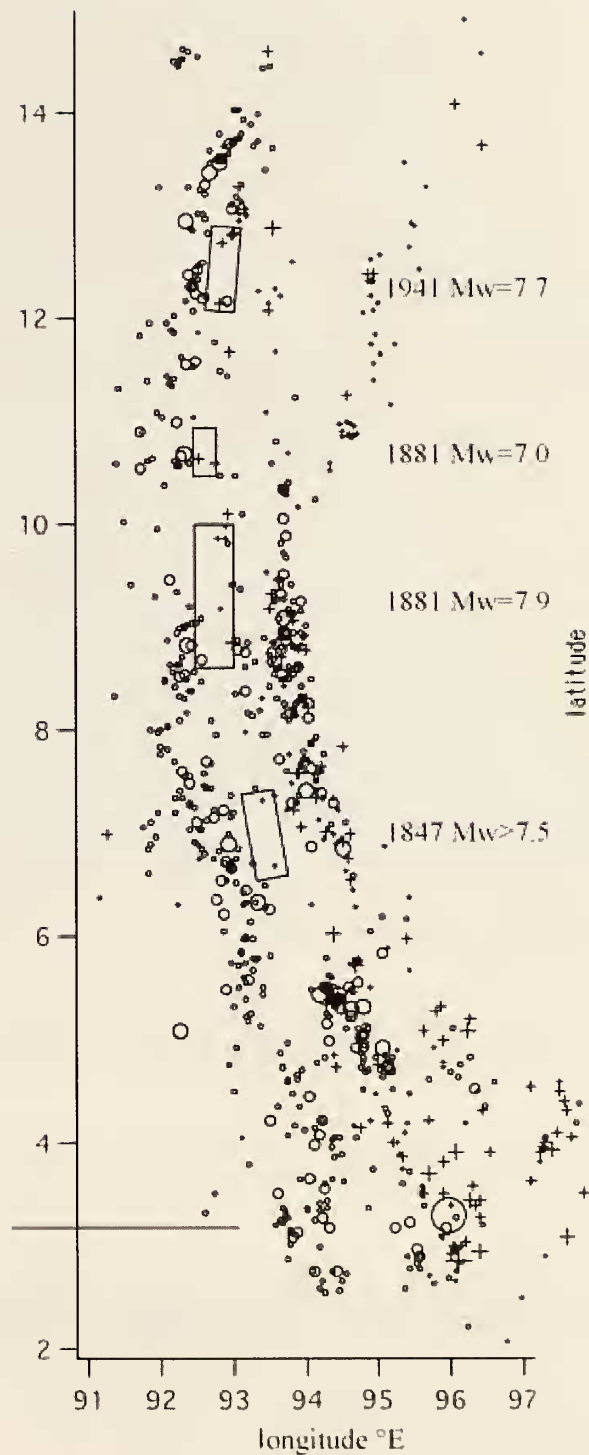


Figure 2. Fault structures of Sumatra (after Malod and Mustafa Kemal, 1996 and Hutchinson, 2005).

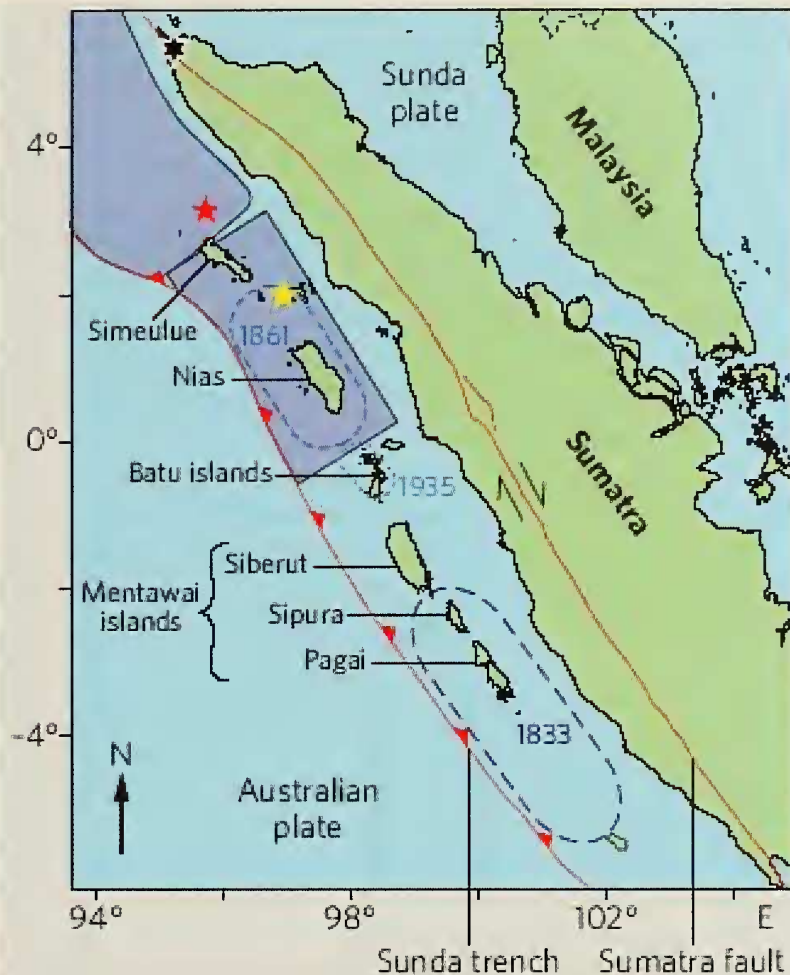




**Figure 3.** Large historical earthquakes between 2 and 14°N. Open circles are aftershocks to 14 January 2005 following the 26 December 2004 earthquake and crosses are seismic events (mostly  $M > 5.5$ ) 1964–2004) (after Bilham et al., 2005).

Table 1. Earthquakes ‘definitely’ or ‘probably’ generating Indian Ocean tsunamis along the Sunda Arc between 5°S and 13°N, 1797-2005.

Date	Mag.	Location	Latitude	Longitude	Depth of Earthquake (km)	Slip along megathrust (m)	Tsunami run-up (m)	Source/s
10/2/1797	8	W Sumatra	- 1.00	99.00		a few metres		NGDC 2005, Nalbent <i>et al.</i> 2005
24/11/1833	8.2	SW Sumatra	- 3.50	102.20		10 to 13		NGDC 2005, Zachariassen <i>et al.</i>
	1999,							Nalbent <i>et al.</i> 2005
5/1/1843	7.2	W Sumatra	1.50	98.00				NGDC 2005
31/10/1847	7.9	Little Nicobar	7.33	93.67				NGDC 2005, Bilham <i>et al.</i> 2005
16/2/1861	8.5	W Sumatra	- 1.00	97.50				NGDC 2005
9/3/1861	7	W Sumatra	0.30	99.37				NGDC 2005
26/4/1861	7	W Sumatra	1.00	97.50				NGDC 2005, Nalbent <i>et al.</i> 2005
25/9/1861	6.5	W Sumatra	- 1.50	100.00				NGDC 2005, Nalbent <i>et al.</i> 2005
19/8/1868		Andamans	11.67	92.73			4	NGDC 2005, Nalbent <i>et al.</i> 2005
31/12/1881	7.9	Car Nicobar	9.00	92.00	15	2.70	1.2	NGDC 2005, Bilham <i>et al.</i> 2005
4/1/1907	7.6	W Sumatra	2.00	94.50			2.8	NGDC 2005
6/2/1908	7.5	SW Sumatra	- 5.00	100.00			1.4	NGDC 2005
25/9/1931	7.5	SW Sumatra	- 5.00	102.70			31.4	NGDC 2005
28/12/1935	7.9	W Sumatra	0.00	98.25		2.3		NGDC 2005, Nalbent <i>et al.</i> 2005
26/6/1941	8.1	Andamans	12.50	92.50	50	<3		NGDC 2005, Bilham <i>et al.</i> 2005
2/4/1964	7	NW Sumatra	5.90	95.70			0.7	NGDC 2005
24/2/1982	5.4	NW Sumatra	4.37	97.70				NGDC 2005
13/9/2002	6.7	Andamans	13.04	93.07	33			NGDC 2005
26/12/2004	9.3	NW Sumatra	3.32	95.86	20 to 30	11 to 23	34.9	NGDC 2005, Bilham <i>et al.</i> 2005
								McCloskey <i>et al.</i> 2005,
								Stein and Okal 2005b
28/5/2005	8.7	NW Sumatra	2.07	97.01	30			USGS 2005



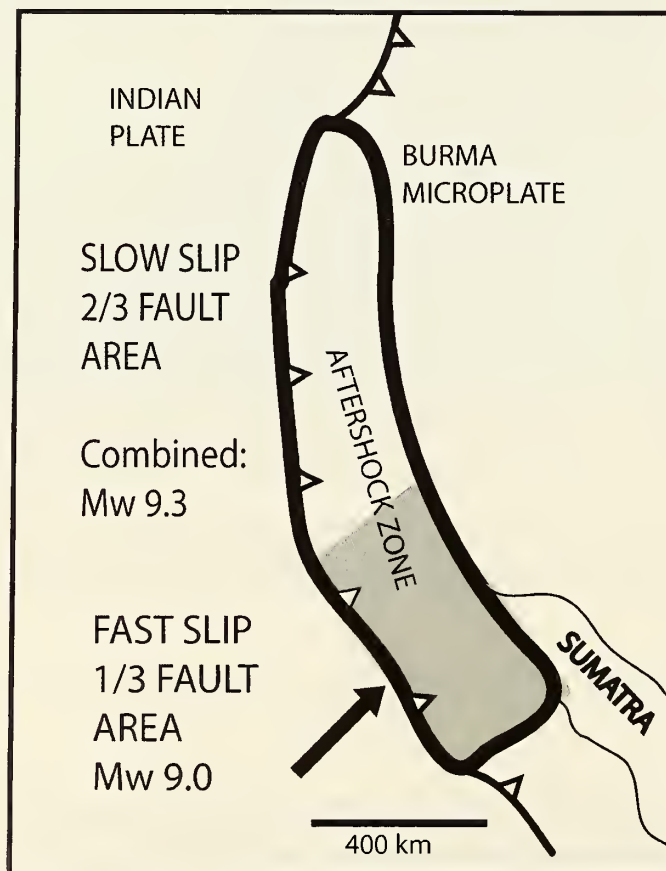
**Figure 4.** Large historical earthquakes between 4°N and 4°S on the Sunda Arc. Dotted lines indicate approximate extents (the 1797 event is not shown but most probably overlaps significantly with the 1833 event). Stars mark locations of epicenter of December 2004 (red) and March 2005 (yellow) events (after Nalbant et al., 2005).

### WHAT HAPPENED: GENERAL CHARACTERISTICS OF THE EARTHQUAKE OF DECEMBER 26, 2004

The 2004 Sumatra–Andaman earthquake was the largest event since the Good Friday Alaskan earthquake of March 27, 1964, and the second largest since modern seismographic recording began a hundred years ago, releasing as much strain energy as all the global earthquakes between 1976 and 1990 combined (Park et al., 2005a). The earthquake’s epicenter located at 3.3°N, near the northern end of the island of Sumatra. The rupture began at 00:58:47 Coordinated Universal Time (UTC) on December 26, 2004 affecting a 100 km section of the plate boundary. After one minute, and for the next four minutes, the “unzipping” of the plate boundary accelerated to a rate of  $3 \text{ km s}^{-1}$  to the



north–northwest before slowing to an extension rate of  $2.5 \text{ km s}^{-1}$  for a further six minutes (Ammon et al., 2005; de Groot-Hedlin, 2005; Ni et al., 2005; Singh, 2005). It passed close to, or through, the rupture zones of the major historic earthquakes of 1847, 1881 and 1941 with apparent indifference (Bilham et al., 2005). Ground movements began in Sri Lanka four minutes after the onset of rupture, the peak-to-peak ground shaking for surface Rayleigh waves at the Global Seismographic Network station at Palkekele, Sri Lanka (station code: PALK) being 9.2 cm (Park et al., 2005a). Particularly remarkable was the slow movement of the northern limit of the rupture, where it took over 30 minutes for the final slippage to be completed in the Andaman Islands. It was this energy release that accounted for one-third of the total energy in the earthquake, resulting in it being upgraded from a moment magnitude of 9.0 to 9.3 and making the earthquake some two and a half-to-three times larger than first reported (Fig. 5; Park et al., 2005b; Stein



**Figure 5.** Areas of “fast slip” and “slow slip” associated with the December 26, 2004 earthquake (after Stein and Okal, 2005b).

and Okal, 2005a, 2005b). Similarly, the total rupture length was 1300 km, trebling the area initially thought to be affected (Stein and Okal, 2005c).

The megathrust occurred at a depth of 20–30 km with the Burma plate rebounding upwards by 10 m at the epicenter. This displaced  $30 \text{ km}^3$  of seawater and, by reducing the volume capacity of the Bay of Bengal and the Andaman Sea through sea floor uplift,

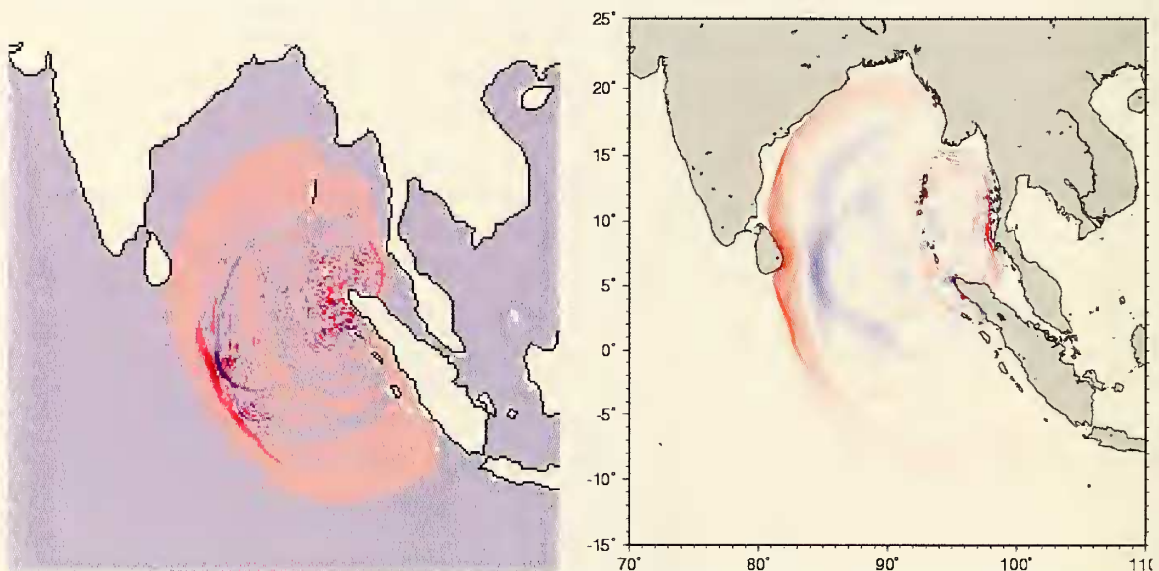
raised global sea level by 0.1 mm (Bilham, 2005). Displacement occurred across a shallow-dipping surface, the western side being uplifted and the eastern side depressed. Gravity changes, seen in remotely sensed geoid anomaly patterns, suggest a 60 km–wide zone of uplift of ca. 2.5 m over a distance of 1000 km, flanked to the northeast by a narrower zone of subsidence of ca. 3 m (Sabadini et al., 2005). Uplift of ca. 1.5 m characterized the SW coast of Simeulue Island, totally exposing the former fringing reef (Sieh, 2005). The area of subsidence intersected the coastline of northern Sumatra. Comparison of elevation data pre- and post-tsunami in the city of Banda Aceh indicate subsidence of 0.28–0.57 m, with other coastal locations showing sinking of 1–2 m (USGS, 2005a).

There is evidence throughout the Nicobar and Andaman islands of considerable changes in land level following the earthquake. At the southernmost tip of Great Nicobar, the benchmark provided by the foundations of the Indira Point lighthouse indicates subsidence of 4.25 m (although see also Ramanamurthy et al., 2005 for lower estimates of subsidence on Great Nicobar), with 4 to 7 m of subsidence at Katchall and extensive flooding on neighboring islands (Bilham et al., 2005). At Car Nicobar, the eastern coast subsided by 1–2 m with uplift of up to 1 m on the western shore. This tilting mirrors that experienced in the New Year's Eve earthquake of December 31, 1881 (Oldham, 1884) but of an order of magnitude greater (Ortiz and Bilham, 2003). Little Andaman, Rutland and North Sentinel, Andaman Islands all appear to have been uplifted by 1 to 2 m with the pre-earthquake lagoon at North Sentinel now completely exposed (Bilham et al., 2005). By comparison, Port Blair suffered subsidence, although the exact magnitude is unclear, with reports giving figures of between 0.25 and 2.0 m (Bilham et al., 2005; Ramanamurthy et al., 2005). Finally, the western coast of Middle Andaman and Diglipur, North Andaman were uplifted by 1 to 2 m and 0.5 to 0.8 m respectively (Bilham et al., 2005). Taken together, these data suggest plate boundary slip estimated at 15–23 m in the Nicobar Islands and 5–10 m in the Andamans (Bilham et al., 2005). These estimates are consistent with a predicted 12–15 m of slip based on maximal tsunami run-up statistics, model solutions based on seismic datasets which are best fitted by 11 m of slip (Stein and Okal, 2005b) and 11–14 m of displacement calculated from continuous GPS observations in the region (Ammon et al., 2005; Kahn and Gudmundsson, 2005). In addition, it appears that the earthquake was accompanied by horizontal displacements in the Nicobar and Andaman Islands of 1–4 m (Bilham et al., 2005). Similarly, it has been estimated that the coastline of Sumatra moved by up to 3 m horizontally and the northern end of Simeulue Island by 2 m (NASA, 2005).

### **CONTROL OF TSUNAMI CHARACTERISTICS BY THE SUMATRA-ANDAMAN EARTHQUAKE**

It is sobering to realize that earthquake generation of tsunamis is a highly inefficient process; Lay et al. (2005) have calculated that the energy of the December 2004 tsunami was equivalent to less than 0.5 % of the strain energy released by the faulting. Nevertheless, earthquake characteristics play an important role in determining the magnitude, timing and pathways of tsunamis. In particular, for the December 2004

event there has been discussion as to the relative importance of the energy released in the early and later stages of the earthquake to tsunami dynamics. Bilham (2005) has taken the view that slip occurred too slowly in the last five minutes of the earthquake to have contributed to tsunami generation whereas Stein and Okal (2005c, 2005d) have argued that the late stage “slow slip” helped excite the tsunami. What is clear is that simulation models based on only the southern segment of the rupture zone (e.g., NIO - National Institute of Oceanography, 2005) show maximum tsunami wave heights propagating in a southeasterly direction into the Indian Ocean with lower wave heights on its northern boundary past Sri Lanka, whereas simulations based on activity along the whole fault (e.g., Satake, 2005) show a strong east-west component with weaker amplitudes to the



**Figure 6.** Simulation modelling of the tsunami wave front. Left: based on south segment of rupture only. Right: based on entire fault length, after 100 minutes. (after Stein and Okal, 2005b).

north, into the Bay of Bengal, south (e.g., Cocos Island) and southeast (e.g., eastern Java and Lombok) (Fig. 6).

The catastrophic impacts on the eastern coastline of Sri Lanka and the west coast of mainland SE Asia are clearly visible in these and other simulations (for example, *inter alia*: European Commission, 2005; NOAA, 2005b; Siberian Division of the Russian Academy of Sciences, 2005; USGS, 2005c). Something of a compromise is offered by Lay et al. (2005) who identify the source region for the initial wave front as extending from the epicenter for 600–800 km to the northwest, terminating in the Nicobar Islands. Tsunami amplitudes are greatest perpendicular to generating structures; thus the strong north-south orientation of the faultline over this distance led to the greatest wave energy being in an east-west direction (Fig. 7; Lomnitz and Nilsen-Holseth, 2005). Furthermore, the extension of earthquake activity beyond the northern tip of Sumatra led to more extensive impacts on the coastline of Thailand and southern Myanmar than might have been expected had there been a sheltering effect from the large Sumatran landmass.



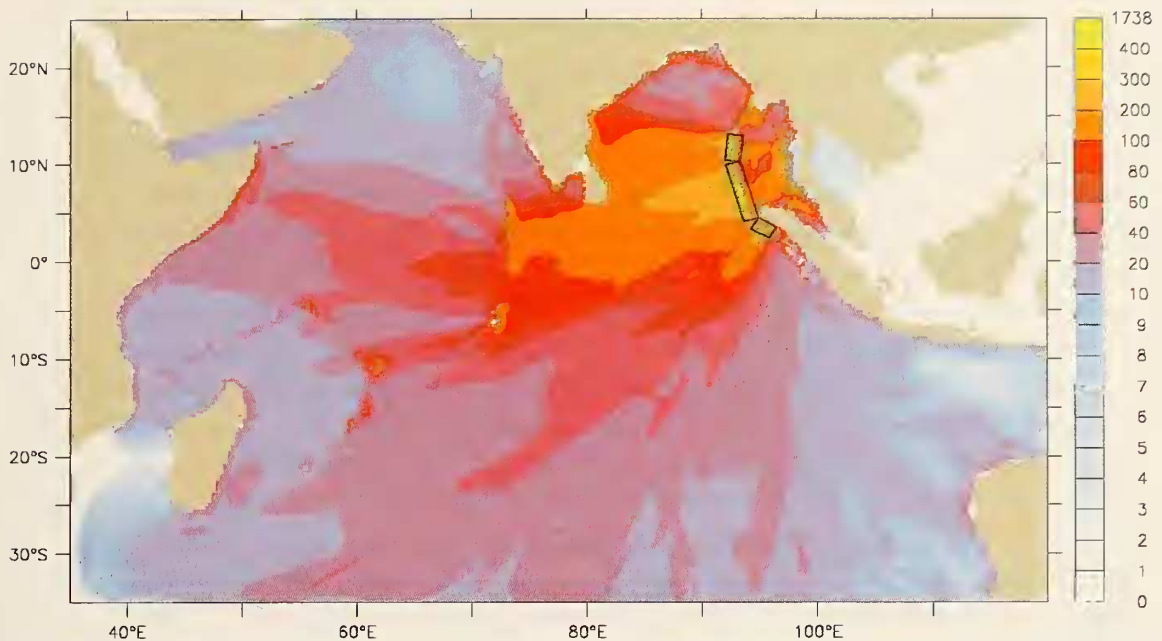


Figure 7. Maximum computed wave heights (cm) in the Indian Ocean (U.S. National Oceanic & Atmospheric Administration (NOAA) and U.S. National Tsunami Hazard Mitigation Program (available at <http://www.pmel.noaa.gov/tsunami/indo20041226/max.pdf>).

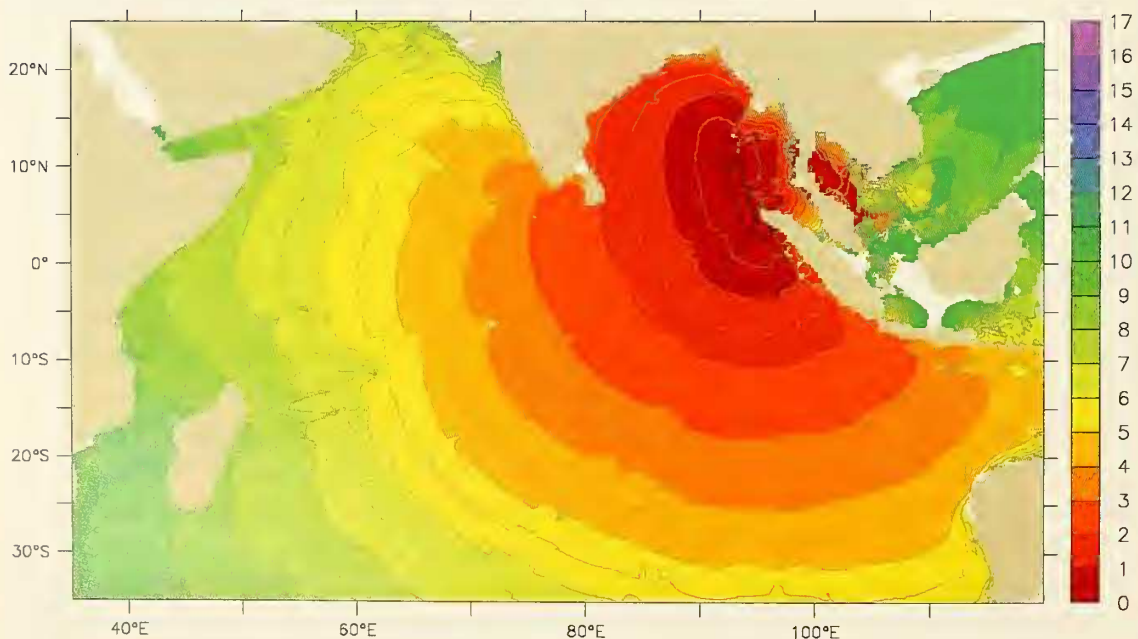
## CHARACTERISTICS OF THE 26 DECEMBER 2004 TSUNAMI

### Travel Times

The Jason 1 altimetry satellite passed over the front of the tsunami wave at 5°S about two hours after the earthquake. Plots of sea surface height changes between this and both preceding and succeeding satellite passes indicate a trough-to-crest tsunami wave height of 1m, a wavelength of 430 km, a wave period of 37 s and a wave velocity of 200 m s<sup>-1</sup> (Gower, 2005). Travel times of the first arrival of the tsunami wave within and around the Indian Ocean basin varied from ca. 30 minutes at Simeulue Island (Yalciner et al., 2005a) and 38 minutes at Port Blair, Andaman Islands (Bilham et al., 2005) to over 14 hours at Cape Town, South Africa. Computed arrival times are shown in Figure 8 and measured arrival times from tide gauge records are reported in Table 2A and B. The northern regions of Sumatra were struck quickly, within one hour of the initial rupture. Tsunami waves reached Sri Lanka, the east coast of India and the Maldives archipelago in ca. 2-3 hours, giving typical propagation speeds of 187 m s<sup>-1</sup> in deep water. Thailand was also struck some 2 hours after the earthquake, despite being closer to the epicenter, because the tsunami travelled more slowly over the shallow eastern margin of the Andaman Sea basin; here propagation speeds were ca. 160 m s<sup>-1</sup>. These figures compare well with the estimates of the velocity of the Krakatau tsunami of 173 m s<sup>-1</sup> (Abercromby et al., 1888). Tsunami waves reached the Seychelles and Mauritius in ca. 7 hours and the coast of East Africa in ca. 9 hours. NOAA (2005b) animations show ocean basin scale refraction of the tsunami wave front around southeastern Sri Lanka and southern India. Of the three major wave trains to affect Sri Lanka, the first two waves, 3 to 4 hours after the earthquake, were refracted around the southern tip of the island whilst the third wave,

after ca. 6 hours, appears to have been reflected from the coast of India (Fernando et al., 2005; Liu et al., 2005). Waves arriving on the NE coast of Penang Island in the Strait of Malacca were reflected from the mainland (Yalciner et al., 2005b). Modelling also shows smaller scale refraction effects in the Maldives, Chagos Archipelago and across the Mascarene Plateau between Seychelles and Mauritius. Wave refraction patterns across the shallow Seychelles Bank resulted in wave convergence in the lee of the island of Mahé (Jackson et al., 2005).

Tsunami waves travelled into both the Atlantic and Pacific Oceans. The tsunami passed around Australia's southern coastline and moved northwards, being recorded in the tide gauge at Kembla, New South Wales and at several stations along the Queensland coast (Queensland Government, 2005), and eastwards, reaching New Zealand 16.5–17 hours (NIWA, 2005) to 18 hours (Mulgor Consulting Limited, 2005) after the earthquake. The tsunami signal was detected in tide gauge records at Valparaiso, Chile and at Callao, Peru after 24 and 31 hours respectively (Fisheries and Oceans Canada, 2005). In the North Pacific Ocean, arrival times in the Hawaiian Islands were after ca. 30 hours with the highest wave heights varying between 0.085 and 0.3 m. First arrivals occurred after 32.5 hours at La Jolla, California, ca. 37 hours at Vancouver Island, British Columbia, 39 hours at Kodiak, Alaska and 41 hours in the North Kuril Islands (Rabinovich, 2005a; Fisheries and Oceans Canada, 2005). In the Atlantic Ocean, the tsunami was recorded at Arraial do Cabo, Rio de Janeiro, Brazil after 22 hours (Candella, 2005), at St. Helena after 25 hours and after 31.5 hours at Halifax, Nova Scotia, Canada where the amplitude was 0.43 cm and the wave period 45 minutes (Fisheries and Oceans Canada, 2005). At Newlyn, Cornwall, UK a small signal after ca. 31 hours was followed by a larger wave train of wave height 0.43 cm and wave period 45–60 minutes after 37.5 hours (Rabinovich, 2005b).



**Figure 8.** Computed arrival time of first wave (hours) in the Indian Ocean (U.S. National Oceanic & Atmospheric Administration (NOAA) and U.S. National Tsunami Hazard Mitigation Program (available at <http://www.pmel.noaa.gov/tsunami/indo20041226/TT.pdf>).

Table 2A. Tsunami of 26 December 2004: travel times (< 5 hours) and water level change.

Location		Travel Time	Height (m)	Source
Belawan	Indonesia	00.41	0.51	Merrifield <i>et al.</i> 2005
Sibolga	Indonesia	01.21	0.43	Merrifield <i>et al.</i> 2005
Lembar	Indonesia	01.51	0.15	Merrifield <i>et al.</i> 2005
Cocos	Australia	02.18	0.33	Merrifield <i>et al.</i> 2005
Prigi	Indonesia	02.21	0.15	Merrifield <i>et al.</i> 2005
Chennai	India	02.36	0.77	NIO (2005)
Visakhapatnam	India	02.36	1.51	NIO (2005)
Colombo	Sri Lanka	02.53	2.17	Merrifield <i>et al.</i> 2005
Panjang	Indonesia	03.00	0.11	Merrifield <i>et al.</i> 2005
Matara	Sri Lanka	03:10		Liu <i>et al.</i> 2005
Langkawi	Malaysia	03:15		Yalciner <i>et al.</i> 2005b
Male	Maldives	03.17	1.46	Merrifield <i>et al.</i> 2005
Gan	Maldives	03.21	0.88	Merrifield <i>et al.</i> 2005
Tuticorin	India	03.28	1.19	NIO (2005)
Hanimaadoo	Maldives	03.33	1.71	Merrifield <i>et al.</i> 2005
			(1.80)	(AusAID 2005)
Penang	Malaysia	04:00		Yalciner <i>et al.</i> 2005b
Diego Garcia	BIOT	04.49	0.56	Merrifield <i>et al.</i> 2005

Travel times correspond to the difference between the onset of the earthquake and the time of arrival of the first wave (not necessarily the largest wave). Height is height of the first wave above mean tide.



Table 2B. Tsunami of 26 December 2004: travel times (&gt; 5 hours) and water level change.

Location	Travel Time	Height (m)	Source
Kochi	05.41	0.81	NIO (2005)
Rodrigues	05.41		Merrifield <i>et al.</i> 2005
Mormugao	05.56	0.4	NIO (2005)
Port Louis	06:43 – 07:47		Merrifield <i>et al.</i> 2005
Hillarys	06.59	0.35	Merrifield <i>et al.</i> 2005
Saladah	07.13	0.28	Merrifield <i>et al.</i> 2005
Pt La Rue	07.17	1.09	Merrifield <i>et al.</i> 2005
Esperance	07.58	-0.01	Merrifield <i>et al.</i> 2005
Lamu	08.57	0.28	Merrifield <i>et al.</i> 2005
Zanzibar	09.45	0.29	Merrifield <i>et al.</i> 2005
Portland	09.49	0.17	Merrifield <i>et al.</i> 2005
Richard's Bay	11.04	0.16	Merrifield <i>et al.</i> 2005
Port Elizabeth	12.22	0.26	Merrifield <i>et al.</i> 2005
Dumont D'Urville	13.34	0.06	Merrifield <i>et al.</i> 2005
Cape Town	14.02	0.1	Fisheries and Oceans
			Canada Science (2005)

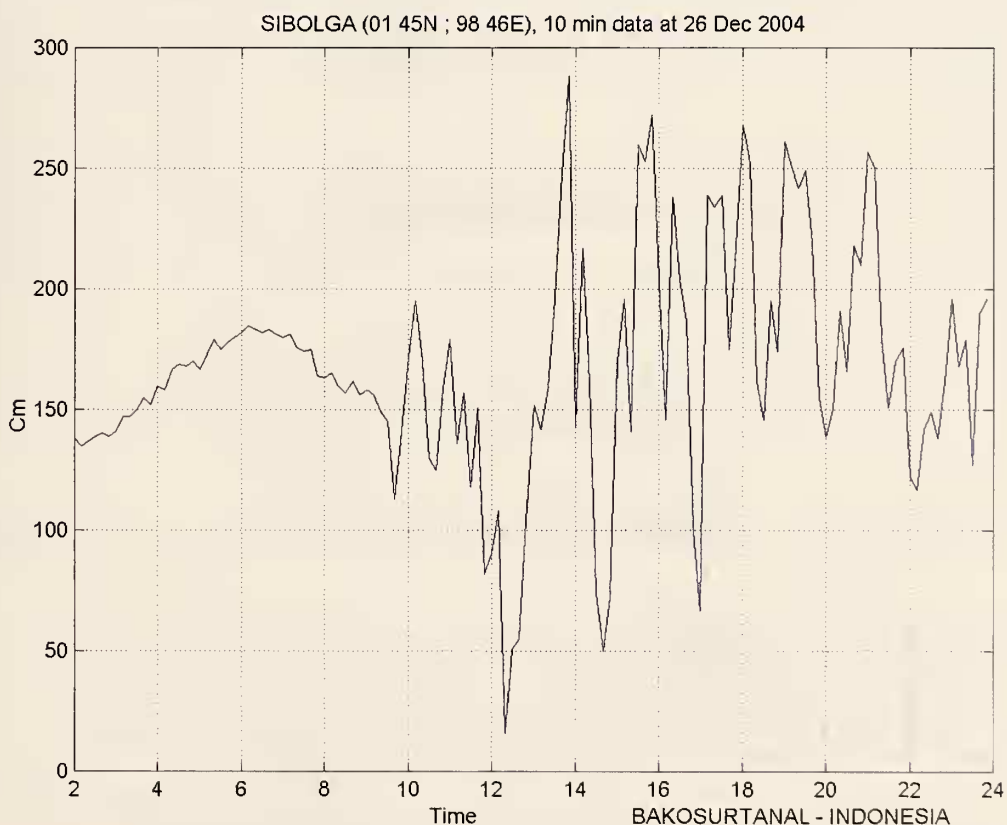
Travel times correspond to the difference between the onset of the earthquake and the time of arrival of the first wave (not necessarily the largest wave). Height is height of the first wave above mean tide.

Rodrigues: last transmitted data as station destroyed by tsunami; Port Louis: time interval corresponding to period of data gap.

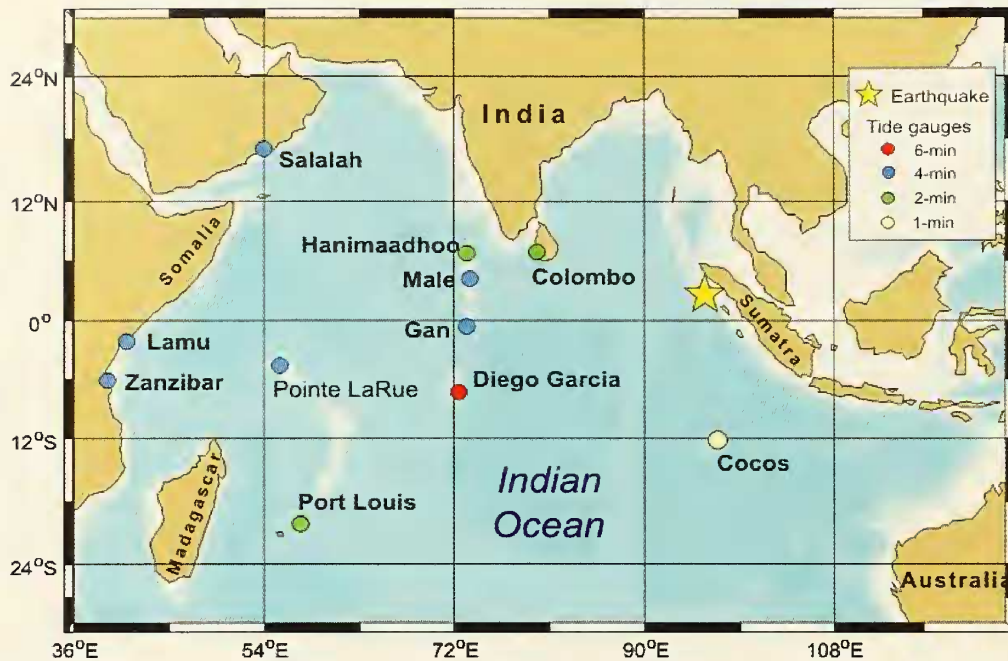
### Wave Characteristics: Tide-Gauge Records

Satellite altimetry recorded typical open-ocean height increases of + 0.6 m two hours after the earthquake (NOAA, 2005a). Merrifield et al. (2005) have detailed tide gauge observations from 23 Indian Ocean stations, recording typical amplitudes of 0.1 to 0.5 m at relatively sheltered port and harbor locations in Indonesia (e.g., Fig. 9), Australia and East Africa (for selected stations see Fig. 10) but with peak water levels of 0.9–1.7 m in the Maldives (Fig. 11) and a maximum amplitude of 2.17 m at Colombo, Sri Lanka (Fig. 11).

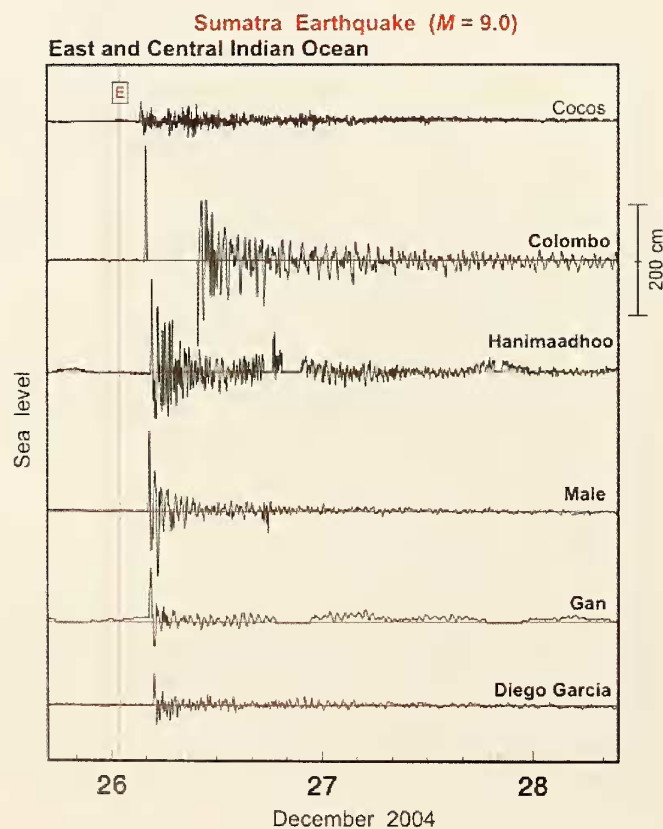
To the east of the rupture, the tsunami signal was initially seen in the form of a wave trough. Thus at Sibolga, western Sumatra, a drop of 0.25 m (Merrifield et al., 2005) to 0.32 m (Kawata et al., 2005) was observed initially, then followed by a water-level rise of 0.82 m. This sequence was followed by a trend of falling sea level, totalling 1.79 m over the next two hours prior to a dramatic rise in water level of 2.72 m. A series of oscillations with an amplitude of over 1 m characterized the succeeding six-hour period (Fig. 9; Kawata et al., 2005).



**Figure 9.** Water-level variations (10-minute interval) at Sibolga, western coast of Sumatra, December 26, 2004 (after Kawata et al., 2005).



**Figure 10.** Tide-gauge stations with tsunami records in the Indian Ocean (source: Fisheries and Oceans Canada, 2005).

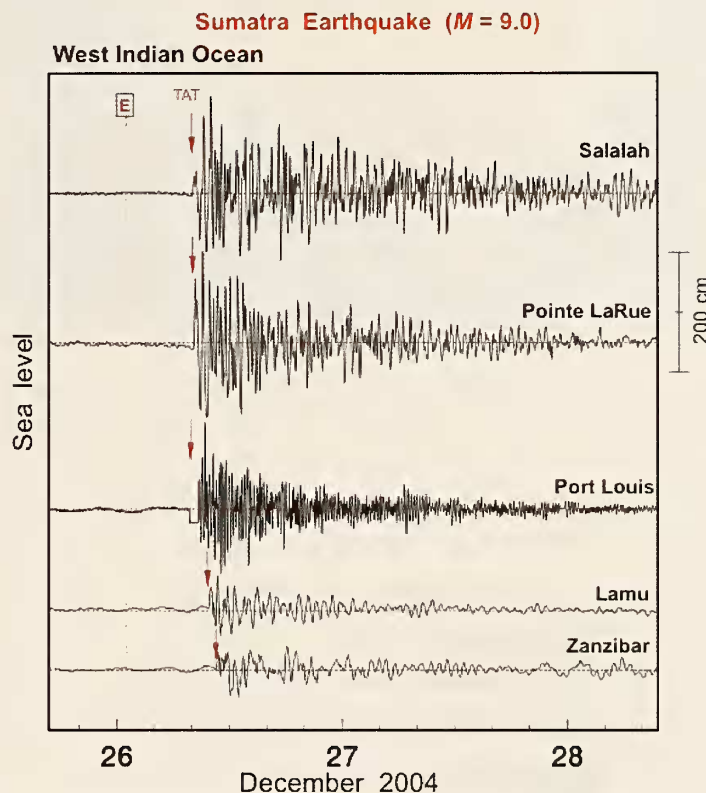


**Figure 11.** Tide-gauge records of the December 2004 tsunami in the Eastern and Central Indian Ocean (source: Fisheries and Oceans Canada, 2005). For locations see Figure 10. Note vertical scale.



To the west of the epicenter all locations first experienced a wave crest. The first wave, however, was not always the largest in the group; at several sites the second or third wave was the largest. At Zanzibar (Fig. 12) and at tide gauges on the South African coast (Figs. 13 and 14), the largest waves arrived six to eight hours after the first wave, while at Portland, Australia larger waves were seen 9 hours after the first arrival with the largest wave recorded as long as 15 hours after the initial impact (Merrifield et al., 2005).

At most locations the waves continued for hours to days after the initial impact (e.g., Colombo, Hanimaadhoo, Fig. 11), indicating the possibility of wave reflections at an Indian Ocean basin scale (e.g., Van Dorn, 1984). At the inter-regional scale, however,



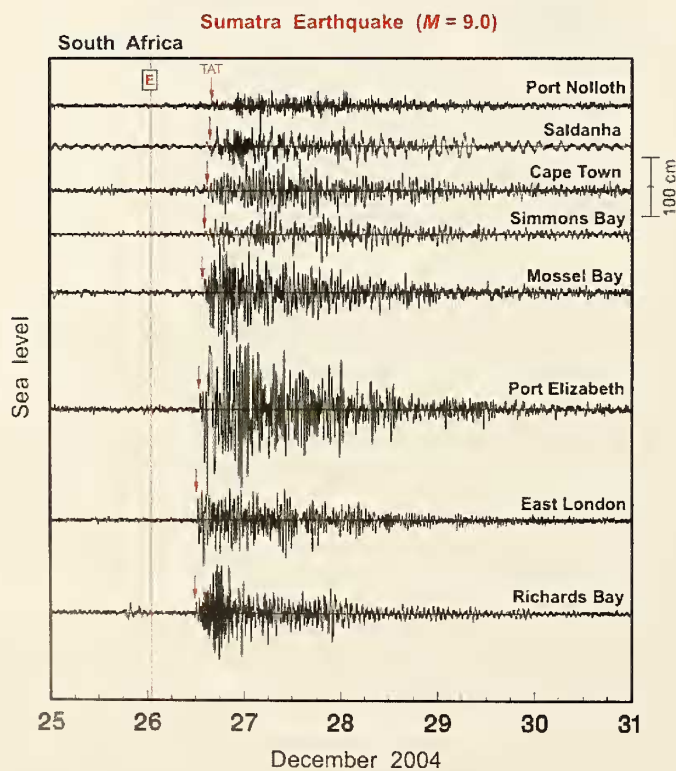
**Figure 12.** Tide-gauge records of the December 2004 tsunami in the Western Indian Ocean (source: Fisheries and Oceans Canada, 2005). For locations see Figure 10. Note vertical scale.

mid-ocean basin station (e.g., Male, Gan, Diego Garcia) water-level records contained ongoing oscillations which were very small compared to the initial waves (Fig. 12). In the Maldives, the first wave was the largest and most sustained and the atolls were subject to “rapid surges of water rather than the large waves experienced in Thailand and Sumatra” (AusAID, 2005, 3).

By comparison, tide-gauge records from locations as geographically dispersed as Oman (e.g., Salalah, Fig. 12) western Australia, eastern Cape, South Africa (Fig. 14; Merrifield et al., 2005) and around Vancouver Island on the Pacific Ocean west coast (Rabinovich, 2005b), showed oscillations of similar amplitude persisting for one to two days. Such signals probably resulted from resonant water level oscillations, with a period of 20–45 minutes, associated with continental shelf bathymetries.



**Figure 13.** Tide-gauge stations with tsunami records in South Africa (source: Fisheries and Oceans Canada, 2005).



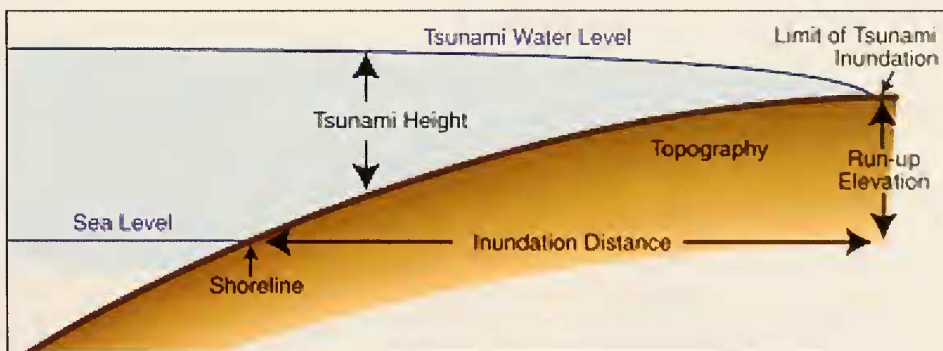
**Figure 14.** Tide-gauge records of the December 2004 tsunami in South Africa (sources: Farre, 2005; Fisheries and Oceans Canada, 2005). For locations see Figure 13. Note vertical scale.

## Relation to Tidal Levels

The tsunami was superimposed on a mixed (diurnal and semidiurnal) tidal signal. In general, the arrival time of the initial tsunami waves coincided with low- or mid-tide. However, in some locations, the arrivals coincided with high tide, as at Vishakpatnam and Chennai, India (NIO, 2005); Langkawi and Penang Islands, Malaysia (Yalciner et al., 2005b), Port Louis, Mauritius and Port Elizabeth, South Africa (Merrifield et al., 2005). On the east coast of Sri Lanka, the tsunami waves coincided with high spring tides and close to the seasonal sea-level maximum but not on the west coast where the tidal phase is opposite to that of the east coast (Merrifield et al., 2005).

## Wave Characteristics: Field Measurements

Table 3 consolidates reports on water-level elevations around the Indian Ocean for the December 2004 tsunami. There is considerable difficulty involved in the construction of a standardized, basin-wide assessment of tsunami physical impacts from the December 2004 event. Firstly, the majority of this information is in the form of non-quantitative visual imagery (often of a most dramatic and unpleasant kind) and where semi-quantitative estimates are available they often take the form of unsubstantiated media reports gathered from eyewitnesses often, literally, running for their lives. It is clear for several locations in Sri Lanka and southern India that these reports resulted in the overestimation of tsunami water depths. Secondly, where quantitative measurements are available it is not always clear as to what the heights quoted refer. Typical measures of tsunami characteristics include inundation distances, run-up elevation (the tsunami's height above mean sea level at its limit of penetration inland) and tsunami wave height (Fig. 15). There is frequent confusion between tsunami run-up and tsunami wave height in the various reports available. Run-up statistics are robust but not always easy to ascertain, particularly in the aftermath of such a humanitarian tragedy. They also require field measurements to be related to benchmarks (themselves often buried or destroyed by the event itself) or related to actual water levels where a knowledge of tidal stage is required.



**Figure 15.** Field survey measurements of tsunami characteristics (from USGS available at <http://soundwaves.usgs.gov/2005/03>).

Table 3. Water level elevations around the Indian Ocean reported from the tsunami of 26 December 2004.

Location	Height of Tsunami Run-up / Inundation (m)	Source	Comments R = run-up I = inundation M = media report
<i>Indonesia</i>			
Banda Aceh, city and island	4.25 – 12.20	NGDC (2005)	R
Kreung Raya	5.10 – 6.71	Tsuji <i>et al.</i> (2005)	I
Sabang	3.02 – 6.20	Tsuji <i>et al.</i> (2005)	I
Rhifing, Banda Aceh	48.86	Shibayama <i>et al.</i> (2005)	I
Aceh Province, west coast	20.00 – 34.90	NGDC (2005)	R
Meulaboh	9.0 – 15.0	Yalciner <i>et al.</i> (2005)	I
Simeulue Island	1.3 – 15.0	Yalciner <i>et al.</i> (2005), Siberian Division, Russian Academy of Sciences (2005)	I / R
Nias Island	4.5 – 5.3	Siberian Division, Russian Academy of Sciences (2005)	R
Sigli	3.68 – 4.82	Tsuji <i>et al.</i> (2005)	I
Medan	1.7 – 2.5	Yalciner <i>et al.</i> (2005)	I
<i>Nicobar / Andaman Islands</i>			
Great Nicobar	3.0 – 6.0	Ramanamurthy <i>et al.</i> (2005)	R
Car Nicobar	7	Ramanamurthy <i>et al.</i> (2005)	R
Little Andaman	5	Ramanamurthy <i>et al.</i> (2005)	R
South Andaman	2.9 – 4.5	Ramanamurthy <i>et al.</i> (2005)	R
Middle Andaman	1.5	Ramanamurthy <i>et al.</i> (2005)	R
North Andaman	1.5 – 5	Ramanamurthy <i>et al.</i> (2005)	R
<i>Thailand</i>			
Khao Lak	4.48 – 9.91	Siberian Division, Russian Academy of Sciences (2005)	R
Phuket (W coast)	2.5 – 5.5	Matsutomi <i>et al.</i> (2005), Siberian Division, Russian Academy of Sciences (2005)	I / R
Phuket (S coast)	2.5 – 3.5	Matsutomi <i>et al.</i> (2005), Siberian Division, Russian Academy of Sciences (2005)	I / R



Table 3 cont. Water level elevations around the Indian Ocean reported from the tsunami of 26 December 2004.

Location	Height of Tsunami Run-up / Inundation (m)	Source	Comments R = run-up I = inundation M = media report
Phuket (E coast)	1 – 3.75	Matsutomi <i>et al.</i> (2005)	I / R
Kho Phi Phi	4.6 – 5.8	Siberian Division, Russian Academy of Sciences (2005)	R
<i>Malaysia</i>			
Langkawi	2.65	Yalciner <i>et al.</i> (2005b)	R
Kedah coast	2.0 – 3.0	NGDC (2005)	R / M
Penang	0.8 – 3.0	Yalciner <i>et al.</i> (2005b)	R
<i>India</i>			
Kavali	>5	NGDC (2005)	R / M
Pulicat	3.2	EERI (2005)	R
Chennai (Madras)	1.4 – 2.8	Ramanamurthy <i>et al.</i> (2005), EERI (2005)	R / M
Kovalam	4.3	EERI (2005)	R
Kalapakkom	4.1	EERI (2005)	R
Periakalapet	3.9	EERI (2005)	R
Puttupatnam, Pondicherry	2.6	EERI (2005)	R
Devanaanpatinam	2.5	EERI (2005)	R
Perangipettinam	2.8	EERI (2005)	R
Tarangambadi, Karaikal	4.4	EERI (2005)	R
Nagappattinam	3.9 – 5.2	Ramanamurthy <i>et al.</i> (2005), EERI (2005)	R / M
Vcdaranniyan	3.6	EERI (2005)	R
Thiruvananthapuram (Trivandrum)	1.5 – 2.0	DOD (2005)	R
Kollam (Quilon)	2.0 – 5.0	DOD (2005)	R
Alappuzha (Aleppey)	1.5 – 2.5	DOD (2005)	R
Kochi (Cochin)	2.0 – 2.5	DOD (2005)	R
Kozhikode (Calicut)	1.5 – 2.0	DOD (2005)	R

Table 3 cont. Water level elevations around the Indian Ocean reported from the tsunami of 26 December 2004.

Location	Height of Tsunami Run-up / Inundation (m)	Source	Comments R = run-up I = inundation M = media report
<i>Sri Lanka</i>			
Kuchchavelli	>3.70	USGS (2005d)	I
Mankerni	>2.00	USGS (2005d)	I
Kalmunai	4.75 – 5.0	USGS (2005d), Headland (2005b)	I/R
Yala	4.5 – 11.3	USGS (2005d), Sato <i>et al.</i> (2005)	I/R
Hambantota	8.8 – 11.0	Sato <i>et al.</i> (2005), Headland (2005b)	I/R
Waligama	4.86	Kawata <i>et al.</i> (2005)	I
Unawatuna	3.3	Sato <i>et al.</i> (2005)	I
Galle	3.24 – 6.03	Kawata <i>et al.</i> (2005)	I
Galle	10.0 – 15.0	NGDC (2005)	R/M
Hikkaduwa	3.4 – 4.73	Sato <i>et al.</i> (2005), Kawata <i>et al.</i> (2005)	I/R
Kahawa	4.08 – 10.04	Kawata <i>et al.</i> (2005)	I
Ambalagoda	4.72	Kawata <i>et al.</i> (2005)	I
Bentota / Beruwala	2.35 – 5.0	Kawata <i>et al.</i> (2005), Headland (2005a)	I/R
Panadura	3.34 – 5.59	Kawata <i>et al.</i> (2005)	I
Moratuwa	3.8 – 4.4	Kawata <i>et al.</i> (2005)	I
Colombo	2.0 – 2.7	Headland (2005a), Sato <i>et al.</i> (2005)	I/I
Negombo / Waikkala	1.6 – 2.7	Sato <i>et al.</i> (2005)	I
Vennapuwa / Marawila	1.8 – 2.3	Sato <i>et al.</i> (2005)	I
<i>Maldives</i>			
Keyodhoo	2.18 – 2.89	Siberian Division, Russian Academy of Sciences (2005)	R
Muli / Rinbudhoo	2.11 – 3.18	Siberian Division, Russian Academy of Sciences (2005)	R
Gemendoo	2.71 – 3.17	Siberian Division, Russian Academy of Sciences (2005)	R
Fanadoo / Kaddhoo	1.28 – 4.43	Siberian Division, Russian Academy of Sciences (2005)	R
Addu Atoll	1.31 – 2.08	Siberian Division, Russian Academy of Sciences (2005)	R

Table 3 cont. Water level elevations around the Indian Ocean reported from the tsunami of 26 December 2004.

Location	Height of Tsunami Run-up / Inundation (m)	Source	Comments R = run-up I = inundation M = media report
<i>Seychelles</i>			
Mahé	1.6 – 4.4	Jackson <i>et al.</i> (2005)	I
Praslin	1.8 – 3.6	Jackson <i>et al.</i> (2005)	I
<i>Somalia</i>			
Bargaal	5	Fritz and Borrero (2005)	R
Xaafuun	4.5	Fritz and Borrero (2005)	R
Foar	5.0 – 7.0	Fritz and Borrero (2005)	R
Bandarbeyla	5.0 – 8.0	Fritz and Borrero (2005)	R
Eyl	5.0 – 9.0	Fritz and Borrero (2005)	R

The measurement of tsunami wave height clearly varies with distance from the shoreline, given the decay of tsunami height with distance inland and the varying frictional resistances from topography, vegetation and buildings to tsunami waves for impacts at the same distance from the shore. There is also a need to distinguish between the highest point reached by breaking waves on exposed coasts, marked by debris lines and bark and leaf stripping on standing trees, and the record of still water levels, often marked in more sheltered settings by water lines on buildings and other structures. Thirdly, it is clear that all these characteristics varied greatly at a regional-to-local level with coastline orientation, bathymetry (e.g. presence / absence of submarine canyons), coastal geology and topography (e.g., headlands v. embayments) causing significant variations in wave focussing, shoaling and refraction, and with coastal plain topography, ecology and settlement patterns (including coastal defence structures), influencing penetration distances and styles of inundation. Finally, effects were further mediated at the small scale with the passage of the tsunami waves over, around and through individual buildings and infrastructure. The view that the loss and degradation of natural ecosystems at the coast under severe human exploitation exacerbated tsunami impacts has been widely promulgated (e.g., UNEP, 2005). A number of short notes have argued that the removal of sand dunes (e.g., at Yala, Sri Lanka (Gibbons et al., 2005)) and mangrove forest (e.g., at Cuddalore, India (Danielsen et al., 2005) and throughout southern Sri Lanka (Dahdouh-Guebas et al., 2005)), and the destruction of coral reefs through coral mining and blast fishing (e.g., between Hikkaduwa to Akuralla, Sri Lanka (Fernando et al., 2005)), locally increased damage and loss of life by creating low resistance pathways to tsunami waves, associated with greater wave heights and increased penetration inland. Although such claims are supported in general terms by mathematical modelling (e.g. Massel et al., 1999), there has been, inevitably, a strong reliance on scattered, largely qualitative observations; a re-appraisal six months after the tsunami concluded that 'evidence so far collected only weakly supports the assertion that coastal wetlands can act as a "green barrier" to protect the coastline and its communities' (Wetlands International, 2005). Furthermore, it has also been argued that where tsunami impacts were particularly severe, the buffering capacity of natural ecosystems was exceeded and did not influence flow depths or inundation distances (Baird et al., 2005).

In the near field, many locations suffered catastrophically high water levels (Table 3). It appears that two tsunami wave crests, from the north and southwest, converged at the northwestern tip of Sumatra. Wave scour and subsidence set back the shoreline at Banda Aceh by up to 1.5 km; eroded sand was deposited in tsunami overwash-type deposits over 70 cm thick in places (USGS, 2005c). Sixty-five kilometers of land between Banda Aceh and Lhoknga were flooded. Flow depths exceeded 9 m at Banda Aceh and inundation reached 3–4 km inland. An inundation height of 48 m has been recorded at Rhiting, Banda Aceh from damage to vegetation and probably records maximum wave height (Shibayama et al., 2005). At Lhoknga, flow depths were in excess of 15 m and tsunami run-up reached 31 m (Borrero, 2005). Elsewhere in this area run-up elevations of 15–30 m were mapped along a 100 km stretch of coastline south to Kreung Sabe (USGS, 2005a), with a maximum recorded run-up to 34.9 m (Tsuji et al., 2005). These high run-ups appear in part to be due to the rapid arrival of the second and third waves after the



initial impact. These subsequent waves overrode the first wave and thus suffered reduced frictional loss allowing greater landward penetration (USGS, 2005c). Further south, at Meulaboh, tsunami run-up continued to exceed 15 m and inundation reached 5 km inland. Offshore, on Simeulue Island, maximum flow depths were 3 m, inundation reached up to 2 km inland and tsunami run-up was also up to 15 m. On the Thai coast, water levels approached 5 m and at Khao Lak, where the town was completely destroyed, almost reached 10 m (there is no readily available information on water levels experienced further north in Myanmar). By comparison, maximum tsunami run-up was only half the 15 m figure on the eastern coast of northern Sumatra, as a result of sheltering effects and shoaling and refraction in the shallow entrance to the Strait of Malacca. The tsunami did not reach Medan until 4 hours after the earthquake, maximum water depths were ca. 1.7 - 2.5 m and inundation distances were less than 1 km (Yalciner et al., 2005a). Similarly, along the west coast of Peninsula Malaysia, flow depths were generally less than 3 m and inundation distances less than 100 m, except where there was penetration into estuaries; the southern limit of the tsunami waves on this coastline was 4°N (Yalciner et al., 2005b).

After Sumatra, the most heavily impacted coastline was that of Sri Lanka. There was a strong patterning to impact at the island scale, with tsunami heights and run-up increasing on the east coast to the south and on the south coast to the east. Peak levels exceeded 11 m in the southeast of the island and levels close to 5 m were reached almost as far west and north as Colombo. At the village of Peraliya, near Hikkaduwa, a 10 m high wave, derailed the engine and eight coaches of the Colombo – Galle express, carrying the train 50 m inland and resulting in over 1500 fatalities. Tide gauge water level variations at Colombo were exceptionally high (Fig. 11) yet this was by no means a severely impacted part of the island. Inundation distances on Sri Lanka reached 1 km where position (southeast coast) and topography (embayments between rocky headlands) concentrated wave attack. At Mankerni on the northeast coast, where impact was modest and inundation depths were less than 2 m, an area 1 m deep and 20–30 m wide was eroded, the sand being deposited 50 m inland as a 10 cm thick tsunami deposit tapering to 2 cm thick at 150 m inland (USGS, 2005d).

On the eastern coast of India, run-up levels typically approached 3–4 m, increasing to over 5 m at Nagappattinam where inundation penetrated 750 m inland. Further south on this coast, run-up levels declined as the coast was effectively sheltered on the leeward side of Sri Lanka. The west coast of India experienced typical run-up elevations of 1.5 to 2.5 m, with local maxima of 5 m.

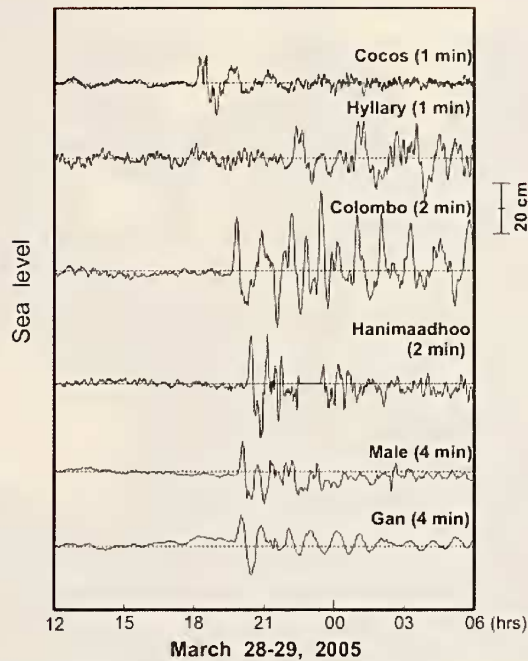
The strong E–W directionality of the tsunami led to run-up elevations in excess of 4 m in the Maldives and of 4.5 to 9 m on the rocky coastline of Somalia. However, the large-scale refraction of the tsunami around Sri Lanka and southern India led to a spreading of the wave crest across the SW Indian Ocean and thus a reduction in wave height in this direction (Table 3). The diminution of the tsunami to the south from Hanimaadhoo in the northern Maldives (ca. 7°N) to Diego Garcia (7°S) is instructive (Fig. 11). Further south and further west, in Mauritius for example, the signal (Fig. 12) was more one of localized flooding on a high tide rather than the kind of destructive wave action seen in Southeast Asia.

## WHAT NEXT: THE MARCH 2005 EARTHQUAKE AND BEYOND

As it now appears that the entire rupture zone slipped in December 2005, the accumulated strain from the subduction of the Indian Plate beneath the Burma microplate has been released, leaving no immediate danger of a comparable tsunami on this segment of the plate boundary. Current estimates of plate convergence across this area suggest that in the vicinity of Port Blair, Andaman Islands a renewal time of 800-1000 years would be required to develop the 10 m of release observed (Bilham et al., 2005), although the much faster convergence rates near the 2004 epicenter suggest a correspondingly shorter interval between major earthquakes of 400 years. However, large earthquakes are often coupled (e.g., Kobe: Toda et al., 1998, Izmit: Stein et al., 1997) as failures spread stresses to other structures in the region. Following the December 24, 2004 rupture, McCloskey et al. (2005) drew attention to increased earthquake risk on both the southerly continuation of the Sunda arc and on the neighboring vertical strike-slip fault system which runs through the island of Sumatra. The threat of failure in the latter remains.

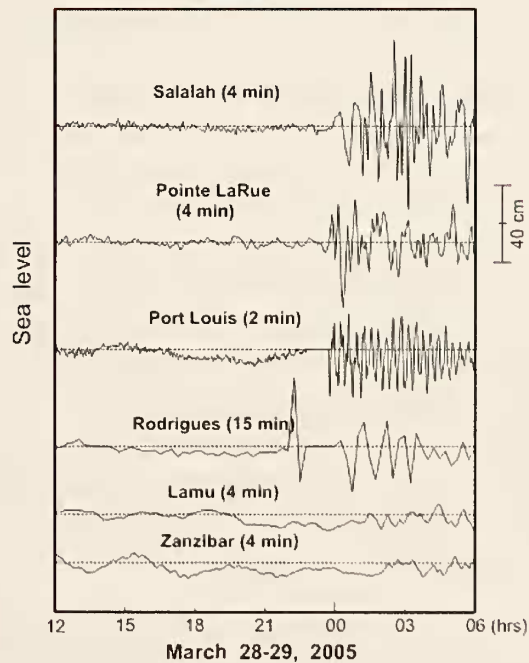
However, it was not unexpected when the Sunda megathrust ruptured again just three months later at 2.1°N under the islands of Simeulue and Nias (160 km southeast of the December 2004 epicenter). The earthquake, with a moment magnitude of 8.7, commenced at 16:09:36 UTC on March 28, 2005 with a rupture-zone length of 300 km (Lay et al., 2005). Ground movements resulted in ca. 1 m of subsidence on the coast of Kepulauan Banyak as well as 1 m of uplift on the coast of Simeulue. At least 1000 people were killed, 300 injured and 300 buildings destroyed on Nias where tsunami run-up heights of 2 m were reported. One hundred people were killed, many injured and several buildings damaged on Simeulue where a 3 m tsunami damaged the port and airport. Two hundred people were killed in Kepulauan Banyak and tsunami run-up heights of 1 m were experienced on the Sumatran coast at Singkil and Meulaboh (USGS, 2005b). However, the tsunami was directed in a southwesterly direction and thus dissipated more harmlessly across the Indian Ocean than the December 2004 waves. Thus, although tsunami wave heights were clearly recorded after the March 2005 event, they were of unremarkable amplitude: ca. 40 cm on Panjang, Indonesia; ca. 25 cm at Colombo, Sri Lanka; and 40 cm on Hanimaadhoo, 18 cm at Male and 10 cm at Gan in the Maldives (Fig. 16; USGS, 2005b). By the East African coast there was almost no signal at all (Fig. 17). This pattern is likely to have similarly characterized the tsunami associated with the great Sumatran earthquake of 1833 (Fig. 18; Cummins and Leonard, 2005).

**Sumatra Earthquake of March 28, 2005 ( $M = 8.7$ )**  
**East and Central Indian Ocean**



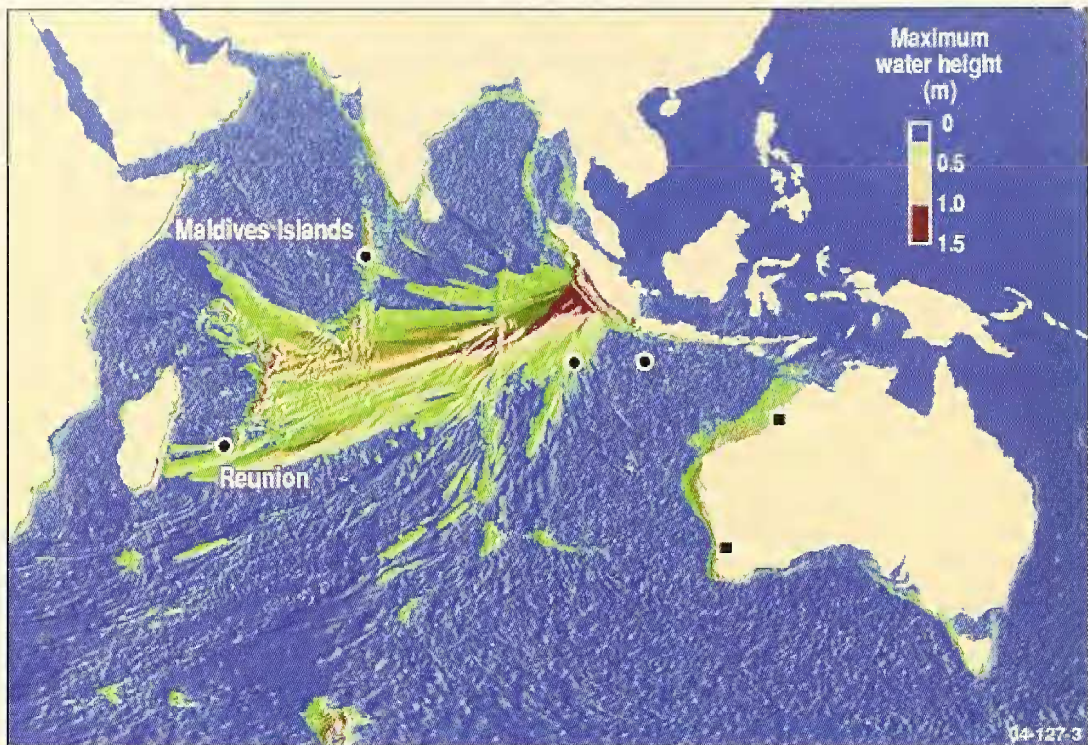
**Figure 16.** Tide-gauge records of the March 2005 tsunami in the Eastern and Central Indian Ocean (source: Fisheries and Oceans Canada, 2005). For locations see Figure 10. Note vertical scale and compare to Figure 11.

**Sumatra Earthquake of March 28, 2005 ( $M = 8.7$ )**  
**West Indian Ocean**



**Figure 17.** Tide-gauge records of the March 2005 tsunami in the Western Indian Ocean (source: Fisheries and Oceans Canada, 2005). For locations see Figure 10. Note vertical scale and compare to Figure 12.





**Figure 18.** Calculated maximum amplitude of the tsunami caused by the 1833 Sumatra earthquake. Most tsunami energy was directed in a southwesterly direction into the open Indian Ocean (Numerical modelling performed by David Burbidge of Geoscience Australia; <http://www.ga.gov.au/ausgeonews/ausgeonews200503/tsunami.jsp>)

This second large earthquake event has now increased stresses to the south of its epicenter. Nalbant et al. (2005) have identified the area beneath the Batu and, particularly, the Mentawai Islands as being at high risk of earthquake and tsunami generation. In the case of the latter island group, the megathrust has not ruptured under the most northerly island of Siberut since 1797, while at Sipura and Pagai, a few meters of slip and 10 m of slip were experienced in 1797 and 1833 respectively. Events similar to the 1833 event appear to have a 230-year cycle and thus the area is approaching the later stages of this cycle. This supposition is confirmed by field observations and stratigraphic analysis of seven microatolls, five from the islands and two from the mainland coast, which indicate that the Mentawai Islands have been submerging at rates of 4-10 mm a<sup>-1</sup> over the last four or five decades, while the mainland has remained relatively stable (Zachariassen et al., 2000). Similar rates of subsidence preceded the 1833 earthquake and tsunami (Zachariassen et al., 1999). Were the next failure to be of comparable magnitude to that of 1833 then further tsunami activity could be a possibility (Nalbant et al., 2005).



## REFERENCES

- Abercromby, R., E.D. Archibald, T.G. Bonney, F.J. Evans, A. Geikie, J.W. Judd, J.N. Lockyer, F.A.R. Russell, R.H. Scott, G.G. Stokkes, R.E. Strachey, G.J. Symons, and W.J.L. Wharton  
 1888. The eruption of Krakatoa, and subsequent phenomena. Report of the Krakatoa Committee of the Royal Society of London. Trubner: London, 525pp.
- Ames, D.  
 2005. ASCE assessment team in India.  
[http://ioc.unesco.org/iosurveys/India/ASCE/ames\\_india.htm](http://ioc.unesco.org/iosurveys/India/ASCE/ames_india.htm)
- Ammon, C.J., C. Ji, H.-K. Thio, D. Robinson, S. Ni, V. Hjorleifsdottir, H. Kanamori, T. Lay, S. Das, D. Helmberger, G. Ichinose, J. Polet, and D. Wald  
 2005. Rupture process of the 2004 Sumatra–Andaman earthquake. *Science* 308:1133–1139.
- AusAID  
 2005. An assessment of damage to Maldivian coral reefs and baitfish populations from the Indian Ocean tsunami prepared by an Australian Government mission and the Maldives Marine Research Centre.  
[http://www.ausaid.gov.au/publications/pdf/maldives\\_reef\\_report.pdf](http://www.ausaid.gov.au/publications/pdf/maldives_reef_report.pdf)
- Baird, A.H., S.J. Campbell, A.W. Anggoro, R.L. Ardiwijaya, N. Fadli, Y. Herdiana, T. Kartawijaya, D. Mahyiddin, A. Mukminin, S.T. Pardede, M.S. Pratchett, E.Rudi, and A.M. Siregar  
 2005. Acehese reefs in the wake of the Asian tsunami. *Current Biology* 15:1926–1930.
- Bannerjee, P., F.F. Pollitz, and R. Burgmann  
 2005. The size and duration of the Sumatra–Andaman earthquake from far-field static offsets. *Science* 308:1769–1772.
- Berninghausen, W.H.  
 1969. Tsunamis and seismic seiches of Southeast Asia. *Bulletin of the Seismological Society of America* 59:289–297.
- Bilham, R.  
 2005. A flying start, then a slow slip. *Science* 308:1126–1127.
- Bilham, R., E.R. Engdhal, N. Feldl, and S.P. Satyabalam  
 2005. Partial and complete rupture of the Indo–Andaman plate boundary 1847–2004. *Seismological Research Letters* 76:299–311.
- Borrero, J.C.  
 2005. Field data and satellite imagery of tsunami effects in Banda Aceh. *Science* 308:1596.
- Bureau of Meteorology, Australian Government  
 2005. Tsunami information.  
[http://www.bom.gov.au/info/tsunami/tsunami\\_info.shtml#dec26](http://www.bom.gov.au/info/tsunami/tsunami_info.shtml#dec26)
- Candella, R.  
 2005. Sea level at Arraial do Cabo, RJ, Brazil.  
<http://www.pmel.noaa.gov/tsunami/indo20041226/IEAPM.htm>

CRISP - Center for Remote Imaging, Sensing and Processing, National University of Singapore

2005. Satellite images of tsunami affected areas.

<http://www.crisp.nus.edu.sg/tsunami/tsunami.html>

Cummings, P., and M. Leonard

2005. The Boxing Day 2004 tsunami – a repeat of the 1833 tsunami? *AusGeo News* 77: 1-5.

<http://www.ga.gov.au/ausgeonews/ausgeonews200503/tsunami.jsp>

Curry, J.R.

2005. Tectonics and history of the Andaman Sea. *Journal of Asian Earth Sciences* 25: 187-232.

Dahdouh-Guebas, F., L.P. Jayatissa, D. Di Nitto, J.O. Bosire, D. Lo Seen, and N. Koedam

2005. How effective were mangroves as a defence against the recent tsunami? *Current Biology* 15:R443-R447.

Danielsen, F., M.K. Sorensen, M.F. Olwig, V. Selvam, F. Parish, N.D. Burgess,

T. Hiraishi, V.M. Karunakaran, M.S. Rasmussen, L.B. Hansen, A. Quarto, and N.

Suryadiputra

2005. The Asian tsunami: A protective role for coastal vegetation. *Science* 310:643.

De Groot-Hedlin, C.D.

2005. Estimation of the rupture length and velocity of the Great Sumatra earthquake of Dec. 26, 2004 using hydroacoustic signals. *Geophysical Research Letters* 32: L11303, doi: 10.1029/2005GL022695.

Department of Ocean Development (DOD)

2005. Preliminary assessment of impact of tsunami in selected coastal areas of India. Department of Ocean Development, Chennai, 42pp.

<http://dod.nic.in/tsunami.pdf>

EERI - Earthquake Engineering Research Institute

2005. December 24 Indian Ocean tsunami EERI-India survey results.

<http://tsunami.oregonstate.edu/Dec2004/eeri/>

European Commission

2005. Joint Research Centre tsunami propagation model.

<http://tsunami.jrc.it/model/>

Farre, R.

2005. Plot-Digital 3-minute data from 8 stations on the coast of South Africa.

<http://www.pmel.noaa.gov/tsunami/indo20041226/SOUTHAF8.htm>

Fernando, H.J.S., J.L. McCulley, S.G. Mendis, and K. Perera

2005. Coral poaching worsens tsunami destruction in Sri Lanka. *EOS* 86:301, 304.

Fisheries and Oceans Canada

2005. December 26, 2004 and March 28, 2005 tsunami events

[http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/tsunami/tsunamiasia\\_e.htm](http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/tsunami/tsunamiasia_e.htm)

Fitch, T.

1972. Plate convergence, transcurrent faults and internal deformation adjacent to Southeast Asia and the Western Pacific. *Journal of Geophysical Research* 77: 4432-4460.

- Fritz, H.M., and J.C. Borrero  
 2005. Field Survey of the Indian Ocean Tsunami on Somalia's Puntland Coast.  
<http://ioc.unesco.org/iosurveys/somalia/somalia.htm>
- Garces, M., P. Caron, C. Hetzer, A. Le Pichon, H. Bass, D. Drob, and J. Bhattacharyya  
 2005. Deep infrasound radiated by the Sumatra earthquake and tsunami. *EOS* 86(35): 317, 320.
- Gibbons, H., J.L. Oates, and B. Jaffe  
 2005. USGS scientists study sediment deposited by 2004 Indian Ocean tsunami.  
<http://soundwaves.usgs.gov/2005/02/>
- Gower, J.  
 2005. Jason 1 detects the 26 December 2004 tsunami. *EOS* 86(4):37-38.
- Gusiakov, V.K.  
 2005. Basic list of measurements made in Sibolga and Nias Island.  
[http://www.pmel.noaa.gov/tsunami/indo20041226/sibolga\\_nias.htm](http://www.pmel.noaa.gov/tsunami/indo20041226/sibolga_nias.htm)
- Headland, J.  
 2005a. 2 February 2005 Report of ASCE/COPRI Sri Lanka team.  
<http://www.asce.org/page/?id=56>
- Headland, J.  
 2005b. 3 February 2005 Report of ASCE/COPRI Sri Lanka team.  
<http://www.asce.org/page/?id=57>
- Hutchinson, C.S.  
 2005. The geological framework in: Gupta A (Ed.) *The Physical Geography of Southeast Asia*. Oxford University Press, Oxford, 3-23.
- Jackson, L.E. Jr., J.V. Barrie, D.L. Forbes, J. Shaw, G.K. Manson, and M. Schmidt  
 2005. Effects of the 26 December 2004 Indian Ocean tsunami in the Republic of Seychelles/ Report of the Canada – UNESCO Indian Ocean Tsunami Expedition, 19 January–5 February, 2005. *Geological Survey of Canada, Open File 4359*, 73pp.
- Kahn, S.A., and O. Gudmundsson  
 2005. GPS analyses of the Sumatra – Andaman earthquake. *EOS* 86(9):89, 94.
- Kawata, Y., H. Hayashi, F. Imamura, S. Koshimura, K. Satake, Y. Tsuji, K. Fujima, I. Hayashi, H. Matsutomi, T. Takahashi, Y. Tanioka, Y. Nishimura, M. Matsuyama, N. Maki, K. Horie, N. Koike, K. Harada, and S. Suzuki  
 2005. The December 26, 2004 earthquake tsunami disaster of Indian Ocean.  
<http://www.drs.dpri.kyoto-u.ac.jp/sumatra/index-e.html#tsunami>
- Lay, T., H. Kanamori, C.J. Ammon, M. Nettles, S.N. Ward, R.C. Aster, S.L. Beck, S.L. Bilek, M.R. Brudzinski, R. Butler, H.R. DeShon, G. Ekstrom, K. Satake, and S. Saplin  
 2005. The Great Sumatra–Andaman earthquake of 26 December 2004. *Science* 308: 1127-1133.
- Liu, P.L.F., P. Lynett, H. Fernando, B.E. Jaffe, H. Fritz, B. Higman, R. Morton, J. Goff, and C. Synolakis  
 2005. Observations by the International Tsunami Survey Team in Sri Lanka. *Science* 308:1595.

Lomnitz, C., and S. Nilsen-Holseth

2005. The Indian Ocean disaster: tsunami physics and early warning dilemmas. *EOS* 86(7): 65, 70.

McCaffrey, R.

1996. Slip partitioning at convergent plate boundaries of SE Asia. In: R. Hall and D. Blundell (eds.) *Tectonic Evolution of Southeast Asia*. Geological Society of London Special Publication 106 (Bath: Geological Society Publishing House), 3-18.

McCloskey, J., S.S. Nalbant, and S. Steacy

2005. Earthquake risk from co-seismic stress. *Nature* 434:291.

Malod, J.A., and B. Mustafa Kemal

1996. The Sumatra margin: Oblique subduction and lateral displacement of the accretionary prism. In: R. Hall and D. Blundell (eds.) *Tectonic Evolution of Southeast Asia*. Geological Society of London Special Publication 106 (Bath: Geological Society Publishing House), 19-28.

Massel, S.R., K. Furukawa, and R.M. Brinkman

2005. Surface wave propagation in mangrove forests. *Fluid Dynamics Research* 24: 219-249.

Matsutomi, H., T. Hiraishi, T. Takahashi, M. Matsuyama, K. Haraada, S. Nakusakul, S. Supartid, W. Kanbua, C. Siwabowon, S. Phetdee, W. Janchoowong, S. Suttiwanakul, and M. Srivichai

2005. The December 26, 2004 Sumatra Earthquake Tsunami, Tsunami Field Survey around Phuket, Thailand.

[http://www.drs.dpri.kyoto-u.ac.jp/sumatra/thailand/phuket\\_survey\\_e.html](http://www.drs.dpri.kyoto-u.ac.jp/sumatra/thailand/phuket_survey_e.html)

Merrifield, M.A., Y.L. Firing, T. Aarup, W. Agricole, G. Brundit, D. Chang-Seng, R. Farre, B. Kilonsky, W. Knight, L. Kong, C. Magori, P. Manurung, C. McCreery, W. Mitchell, S. Pillay, F. Schindele, F. Shillington, L. Testut, E.M.S. Wijeratne, P. Caldwell, J. Jardin, S. Nakahara, F.-Y. Porter, and N. Turetsky

2005. Tide gauge observations of the Indian Ocean tsunami, December 26, 2004. *Geophysical Research Letters* 32:L09603, doi:10.1029/2005GL022610.

Mulgor Consulting Ltd

2005. Sumatra tsunami at New Zealand ports and harbours.

<http://www.mulgor.co.nz/SumatraTsunami/index.htm>

Murty, T.F., and M. Rafiq

1991. A tentative list of tsunamis in the marginal seas of the north Indian Ocean. *Natural Hazards* 4: 81-83.

Nalbant, S.S., S. Steacy, K. Sieh, D. Natawidjaja, and J. McCloskey

2005. Earthquake risk on the Sunda trench. *Nature* 435: 756-757.

NASA - National Aeronautics and Space Administration

2005. Earth Observatory Natural Hazards: Earthquake spawns tsunamis.

[http://earthobservatory.nasa.gov/NaturalHazards/shownh.php3?img\\_id=12646](http://earthobservatory.nasa.gov/NaturalHazards/shownh.php3?img_id=12646)

NGDC - National Geophysical Data Center

2005. Dec 26, 2004 Magnitude 9.0 Earthquake & Tsunami in the Indian Ocean.

<http://www.ngdc.noaa.gov/spotlight/tsunami/tsunami.html>



- NIO - National Institute of Oceanography, India  
 2005. 26 December 2004 tsunami.  
<http://www.nio.org/jsp/tsunami.jsp>
- NIWA - National Institute of Water and Atmospheric Research  
 2005. Sumatra tsunami reached New Zealand.  
<http://www.niwa.co.nz/rc/prog/chaz/news/sumatra>
- NOAA - National Oceanic and Atmospheric Administration  
 2005a. NOAA scientists able to measure tsunami height from space. NOAA News Online, Story 2365.  
<http://www.noaanews.noaa.gov/stories2005/s2365.htm>
- NOAA - National Oceanic and Atmospheric Administration  
 2005b. <http://www.pmel.noaa.gov/tsunami/Mov/TITOV-INDO2004.mov>
- Newcomb, K.R., and W.R. McCann  
 1987. Seismic history and seismotectonics of the Sunda Arc. *Journal of Geophysical Research* 92 (B1): 421-439.
- Ni, S., H. Kanamori, and D. Helmberger  
 2005. Energy radiation from the Sumatra earthquake. *Nature* 434: 582.
- Oldham, R.D.  
 1884. Note on the earthquake of 31 December 1881. *Records of the Geological Survey of India* 17: 47-53.
- Ortiz, M., and R. Bilham  
 2003. Source area and rupture parameters of the 31 December 1881  $M_w = 7.9$  Car Nicobar earthquake estimated from tsunamis recorded in the Bay of Bengal. *Journal of Geophysical Research* 108 (B4):2215.
- Park, J., K. Anderson, R. Aster, R. Butler, T. Lay, and D. Simpson  
 2005a. Global Seismographic Network records the great Sumatra-Andaman earthquake. *EOS* 86(6):57, 60-61.
- Park, J., T.-R.A. Song, J. Tromp, E. Okal, S. Stein, G. Roullet, E. Clevede, G. Laske, H. Kanamori, P. Davis, J. Berger, C. Braitenberg, M. Van Camp, X. Lei, H. Sun, H. Xu, and S. Rosat  
 2005b. Earth's free oscillations excited by the 6 December 2004 Sumatra-Andaman earthquake. *Science* 308:1139-1144.
- Queensland Government  
 2005. Queensland EPA monitors 2004 Asian tsunami: fact sheet.  
<http://www.epa.qld.gov.au/publications?id=1500>
- Rabinovich, A.B.  
 2005b. Residual tide gauge records for Gibraltar and Newlyn.  
[http://www.pmel.noaa.gov/tsunami/indo20041226/tidegauge\\_newlyn.htm](http://www.pmel.noaa.gov/tsunami/indo20041226/tidegauge_newlyn.htm)
- Rabinovich, A.B.  
 2005a. Plot of tsunami records at 6 stations in British Columbia.  
[http://www.pmel.noaa.gov/tsunami/indo20041226/Bc\\_tsu6.htm](http://www.pmel.noaa.gov/tsunami/indo20041226/Bc_tsu6.htm)
- Ramanamurthy, M.V., S. Sundaramoorthy, Y. Pari, V. Ranga Rao, P. Mishra, M. Bhat, Tune Usha, R. Venkatesan, and B.R. Subramanian  
 2005. Inundation of Seawater in Andaman and Nicobar Islands and parts of Tamilnadu

- coast, India, during 2004 Indian Ocean Tsunami.  
<http://ioc.unesco.org/iosurveys/India/nicobar/nicobar.htm>
- Sabadini, R., G. Dalla Via, M. Hoogland, and A. Aoudia  
 2005. A splash in earth gravity from the 2004 Sumatra earthquake. *EOS* 86(15):149, 153.
- Satake, K.  
 2005. Tsunamis in Indian Ocean from Sumatra earthquake.  
<http://staff.aist.go.jp/kenji.satake/Sumatra.html>
- Sato, S., Y. Koibuchi, T. Honda, T. Welhena and S. Ranasinghe  
 2005. 2004 Dec 26<sup>th</sup> tsunami–Sumatra earthquake. Field investigations carried out in Sri Lanka (along the west and south coast of Sri Lanka).  
[http://www.drs.dpri.kyoto-u.ac.jp/sumatra/srilanka-ut/SriLanka\\_UTeng.html](http://www.drs.dpri.kyoto-u.ac.jp/sumatra/srilanka-ut/SriLanka_UTeng.html)
- Shibayama, T., A. Okaysu, J. Sasaki, T. Suzuki, R. Matsumaru, Masimin, and Z. Atiff  
 2005. The December 26, 2004 Sumatra earthquake tsunami, tsunami field survey in Banda Aceh of Indonesia.  
[http://www.drs.dpri.kyoto-u.ac.jp/sumatra/indonesia-ynu/indonesia\\_survey\\_ynu\\_e.html](http://www.drs.dpri.kyoto-u.ac.jp/sumatra/indonesia-ynu/indonesia_survey_ynu_e.html)
- Siberian Division, Russian Academy of Sciences  
 2005. Tsunami laboratory: December 26, 2004 North Sumatra earthquake and tsunami.  
<http://tsun.sssc.ru/tsulab/20041226.htm>
- Sieh, K.  
 2005. Aceh–Andaman earthquake: What happened and what’s next? *Nature* 434: 573-574.
- Simandjuntak, T.O., and A.J. Barber  
 1996. Contrasting tectonic styles in the Neogene orogenic belts of Indonesia. In: R. Hall and D. Blundell (eds.) *Tectonic Evolution of Southeast Asia*. Geological Society of London Special Publication 106 (Bath: Geological Society Publishing House), 185-201.
- Singh, S.C.  
 2005. Sumatra earthquake research indicates why rupture propagated northward. *EOS* 86(48):497, 502.
- Stein, R.S., A.A. Barka, and J.H. Dieterich  
 1997. Progressive failure on the North Anatolian fault since 1939 by earthquake stress triggering. *Geophysical Journal International* 128: 594-604.
- Stein, S., and E. Okal  
 2005a. Sumatra earthquake three times larger than originally thought.  
[http://www.eurekalert.org/pub\\_releases/2005-02/nu-set020705.php](http://www.eurekalert.org/pub_releases/2005-02/nu-set020705.php)
- Stein, S., and E. Okal  
 2005b. Long period seismic moment of the 2004 Sumatra earthquake and implications for the slip process and tsunami generation.  
<http://www.earth.northwestern.edu/people/seth/research/sumatra.html>
- Stein, S., and E. Okal  
 2005c. Speed and size of the Sumatra earthquake. *Nature* 434:581-582.

- Stein, S., and E. Okal  
 2005d. The 2004 Sumatra earthquake and Indian Ocean tsunami: What happened and why. *The Earth Scientist* 21(2): 6-11.
- Toda, S., R.S. Stein, P.A. Reasenber, J.H. Dieterich, and A. Yosida  
 1998. Stress transferred by the 1995 M-w = 6.9 Kobe, Japan, shock: Effect on aftershocks and future earthquake probabilities. *Journal of Geophysical Research* 103(B10):24543-24565.
- Tsuji, Y., H. Matsutomi, Y. Tanioka, Y. Nishimura, T. Sakakiyama, T. Kamataki, Y. Murakami, A. Moore, and G. Gelfenbanm  
 2005. Distribution of the Tsunami Heights of the 2004 Sumatra Tsunami in Banda Aceh measured by the Tsunami Survey Team (The Head: Dr. Tsuji).  
<http://www.eri.u-tokyo.ac.jp/namegaya/sumatera/surveylog/eindex.htm>
- UNEP - United Nations Environment Programme  
 2005. After the tsunami: Rapid environmental assessment. UNEP, Nairobi, 140 pp.
- USGS - United States Geological Survey  
 2005a. Magnitude 8.7 - Northern Sumatra, Indonesia 2005 March 28 16:09:36 UTC Preliminary Earthquake Report.  
<http://earthquake.usgs.gov/eqinthenews/2005/usweax/>
- USGS - United States Geological Survey  
 2005b. Tsunami simulations.  
<http://www.pmel.noaa.gov/tsunami/indo20041226/Geist.htm>
- USGS - United States Geological Survey  
 2005c. The 26 December 2004 Indian Ocean Tsunami: Initial Findings from Sumatra.  
<http://walrus.wr.usgs.gov/tsunami/sumatra05/index.html>
- USGS - United States Geological Survey  
 2005d. The December 26, 2004 Indian Ocean Tsunami: Initial Findings on Tsunami Sand Deposits, Damage, and Inundation in Sri Lanka.  
<http://walrus.wr.usgs.gov/tsunami/srilanka05/index.html>
- Van Dorn, W.G.  
 1984. Some tsunami characteristics deducible from tide records. *Journal of Physical Oceanography* 14:353-363.
- Wetlands International  
 2005. Updated assessment report to Ramsar Standing Committee.  
<http://www.wetlands.org/Tsunami/data/SC31-30%20tsunami.doc>
- Wilson, C.K.  
 2005. Bulletins from HMS Scott.  
[http://www.pmel.noaa.gov/tsunami/indo20041226/hms\\_scott.htm](http://www.pmel.noaa.gov/tsunami/indo20041226/hms_scott.htm)
- Winchester, S.  
 2003. *Krakatoa, the day the world exploded: August 27, 1883*. Harper Collins: New York, 432pp.
- Yalciner, A.C., N.H. Ghazali, and A.K.A. Wahab  
 2005a. December 26, 2004 Indian Ocean tsunami field survey (July. 09-10, 2005) at North West Peninsular Malaysia coast, Penang and Langkawi.  
<http://yalciner.ce.metu.edu.tr/malaysia-survey/yalciner-et-al-malaysia-survey-sep-22-2005.pdf>

- Yalciner, A.C., D. Perincek, S. Ersoy, G.S. Presateya, R. Hidayat, and B. McAdoo  
2005b. December 26, 2004 Indian Ocean tsunami field survey (Jan. 21-31, 2005) at  
north of Sumatra Island.  
<http://ioc.unesco.org/iosurveys/Indonesia/yalciner/yalciner.htm>
- Zachariasen, J., K. Sieh, F.W. Taylor, R.L. Edwards, and W.S. Hantoro  
1999. Submergence and uplift associated with the giant 1833 Sumatran subduction  
earthquake: Evidence from coral microatolls. *Journal of Geophysical Research*  
104(B1):895-919.
- Zachariasen, J., K. Sieh, F.W. Taylor, and W.S. Hantoro  
2000. Modern vertical deformation above the Sumatran subduction zone:  
Paleogeodetic insights from coral microatolls. *Bulletin of the Seismological  
Society of America* 90(4):897-913.